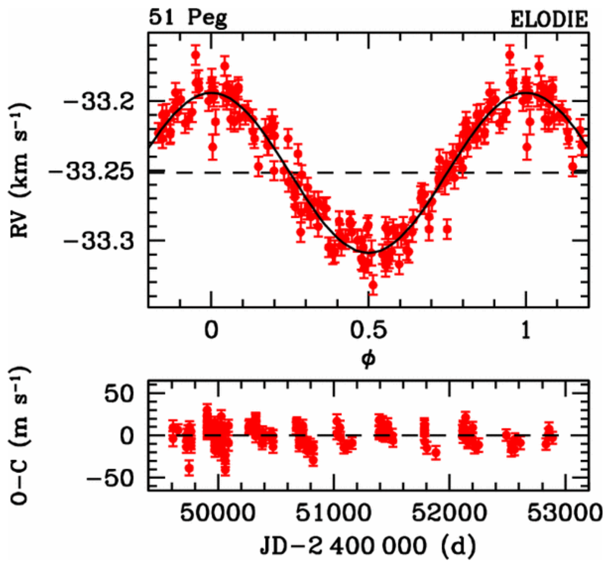
Searching for Earth 2.0s and Life in the Universe

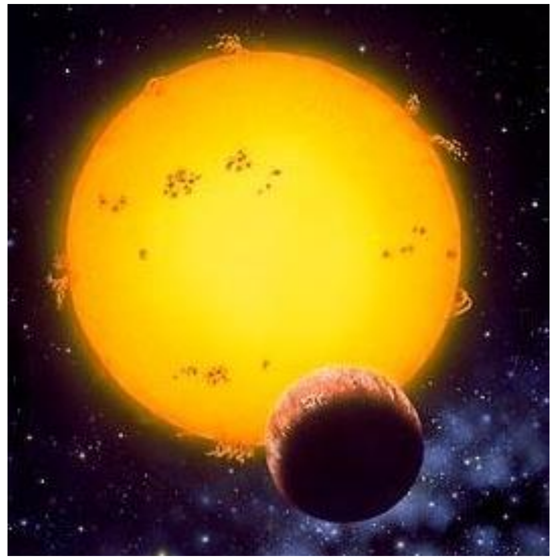
Jian Ge

Shanghai Astronomical Observatory
Chinese Academy of Sciences

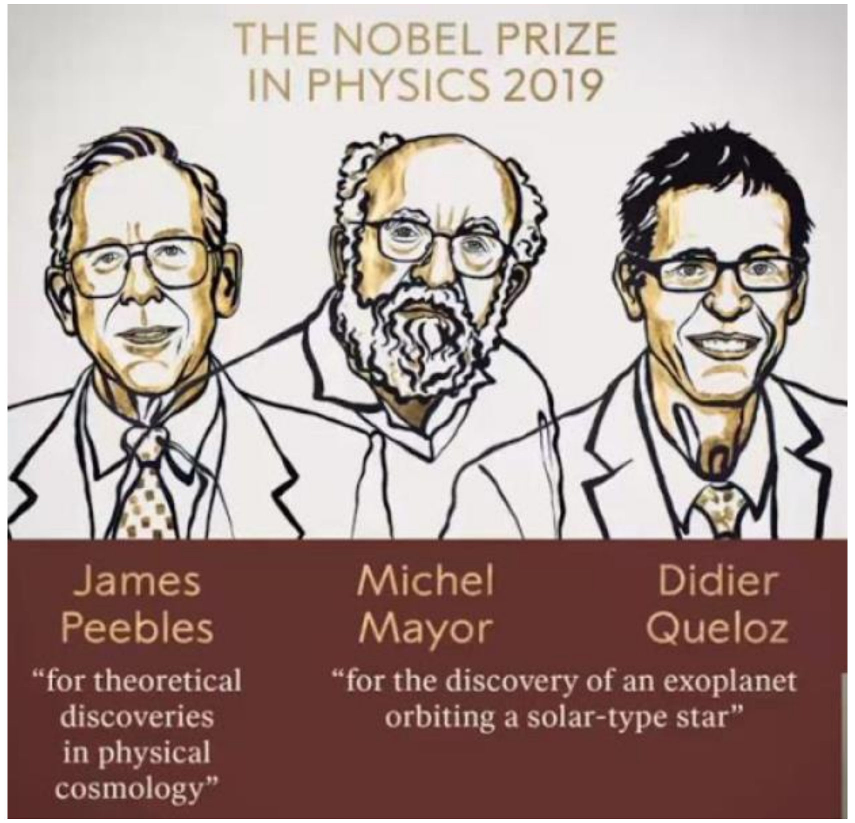
天体力学数学理论研讨会, 11/24/2022

Searching for Earth 2.0s is the Next Major Step





Discovery of a hot Jupiter around a sun-like star, 51 Peg in 1995



The next major step

Earth 2.0s are the holy grails!

Science 125th Anniversary: **125 QUESTIONS: EXPLORATION AND DISCOVERY**

- Are we alone in the universe?
- How do planets form?

Earth 2.0s: Earth-like planets (0.8-1.25$R_\oplus$) around Solar-type Stars

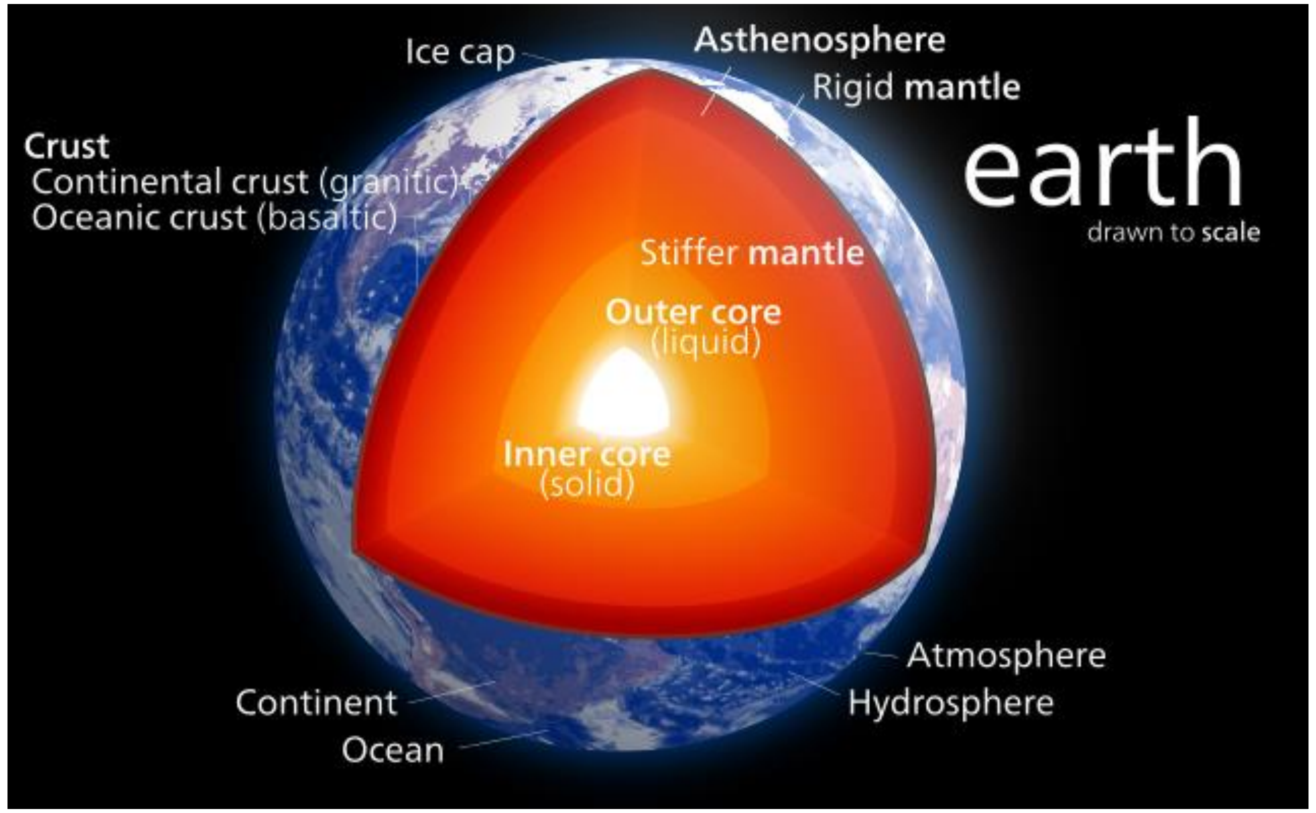
Earth 2.0's Key Properties

Key factors to confirm an Earth 2.0:

1. At a proper distance（1AU） potentially with liquid water on its surface (habitable zone) → Orbital period

2. Proper surface (rocky) and inner structure (such as tectonic motion and magnetic field) → Mass, Size and Density

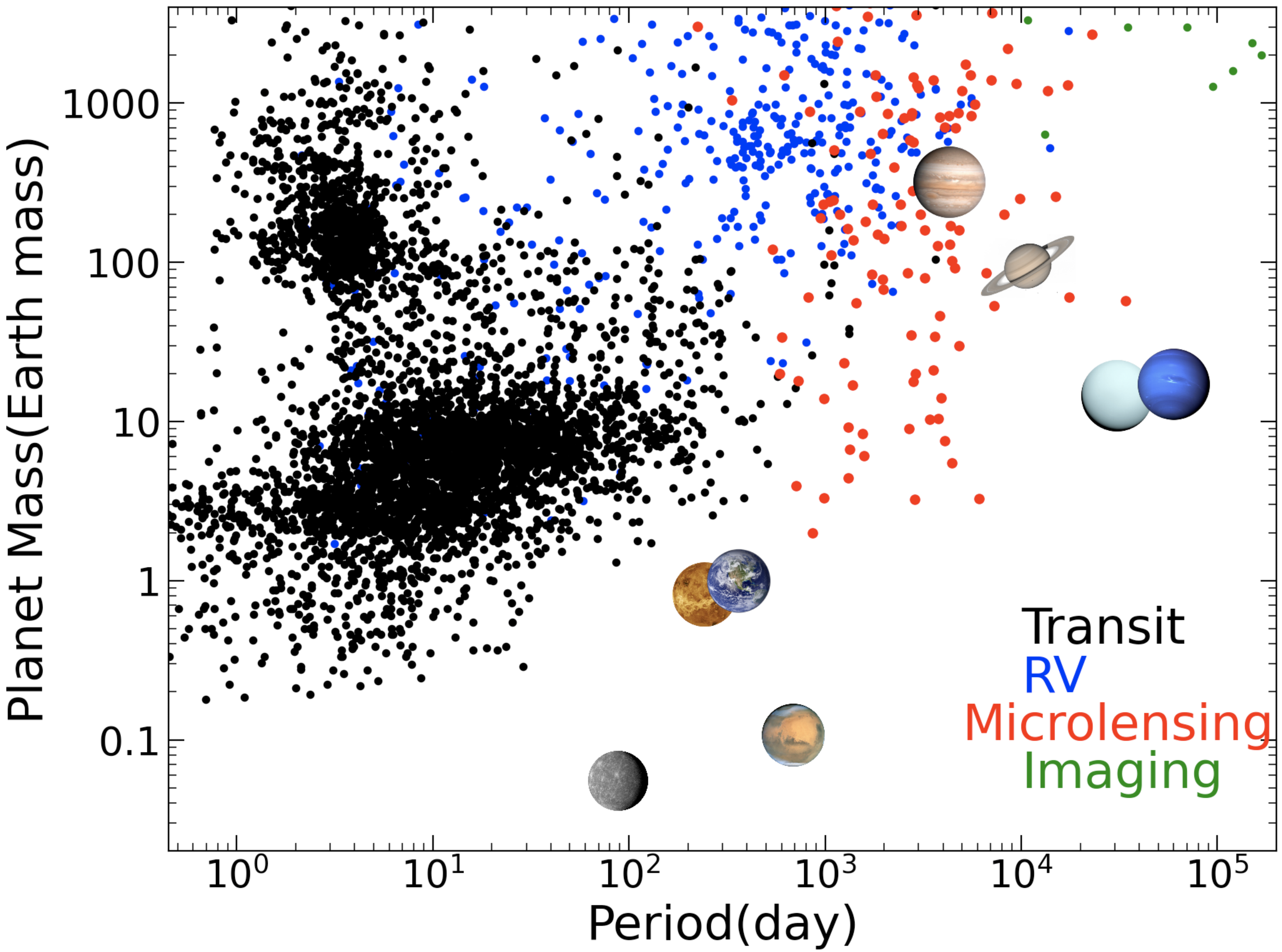
3. Planetary atmosphere has a proper amount of molecules such as water and oxygen →Atmosphere spectra



- Earth 2.0:Mass ~ 0.5-2$M_\oplus$
- Super Earths: Mass~2-10$M_\oplus$

Earth 2.0s： Earth-like planets (0.8-1.25$R_\oplus$) around Solar-type Stars

Current Exoplanet's Landscape (https://exoplanetarchive.ipac.caltech.edu/)

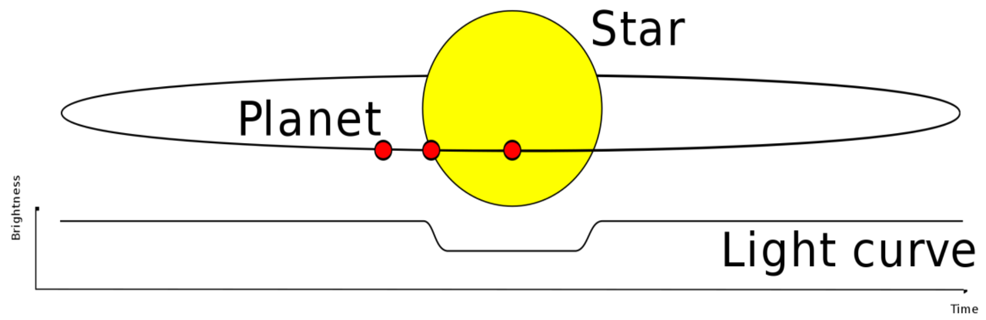


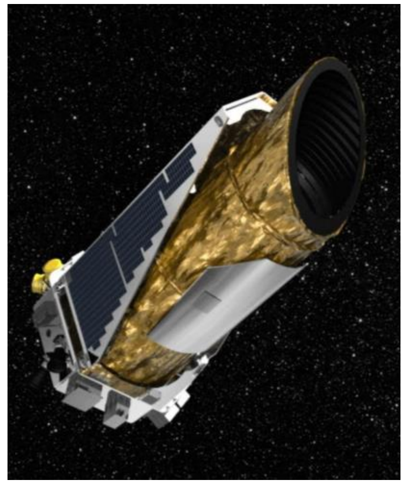
- **No Earth 2.0s have been identified yet!**
- **Two methods can potentially detect Earth 2.0s: Transit and RV methods**
- **Microlensing technique can also detect cold terrestrial planets**

Two Popular Methods Capable of Detecting Earth 2.0s

Transit Method

Detection threshold:
Ratio of Earth to Sun's area (~10^{-4})

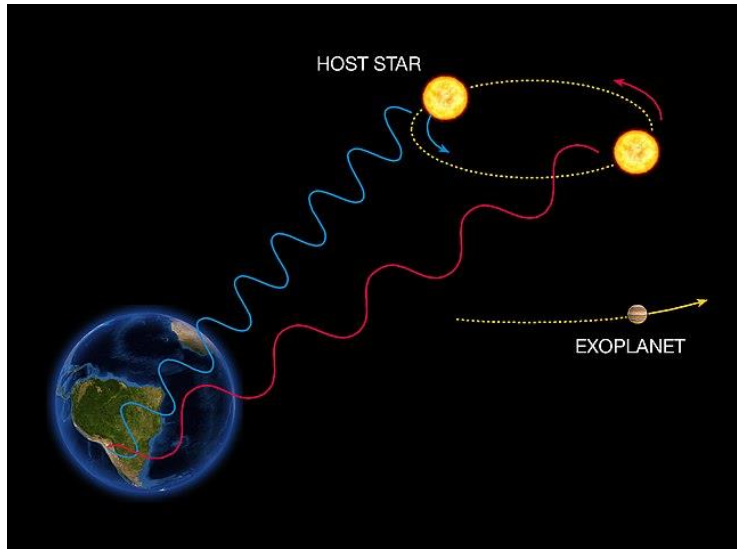


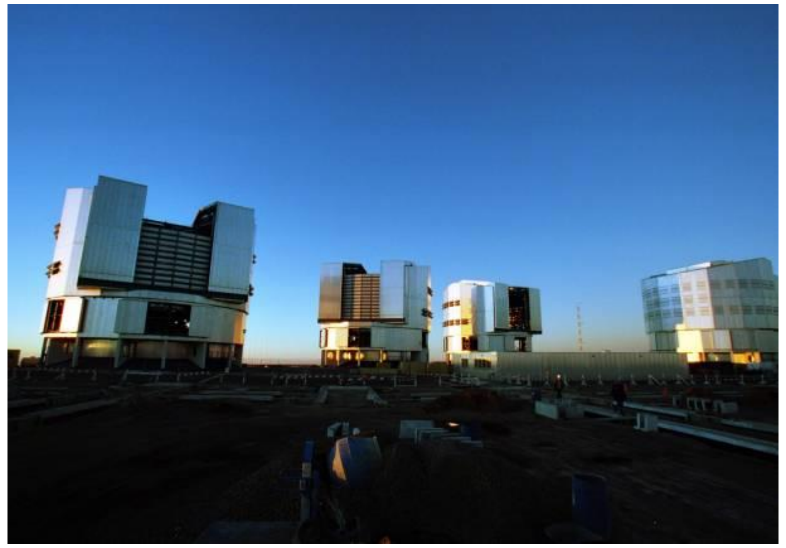


- Earth 2.0's transit signal is weak, requiring ultra-high precision photometry (~34ppm)
- Space photometry required to detect Earth 2.0s
- Kepler and TESS have achieved ~29 ppm and 30 ppm for stars with magnitudes of 12 and 6.5, respectively
- Transit surveys capable of searching for millions of stars simultaneously, increasing detection chance!

RV Method

Detection threshold:
Ratio of Earth to Sun's mass (~10^{-6})

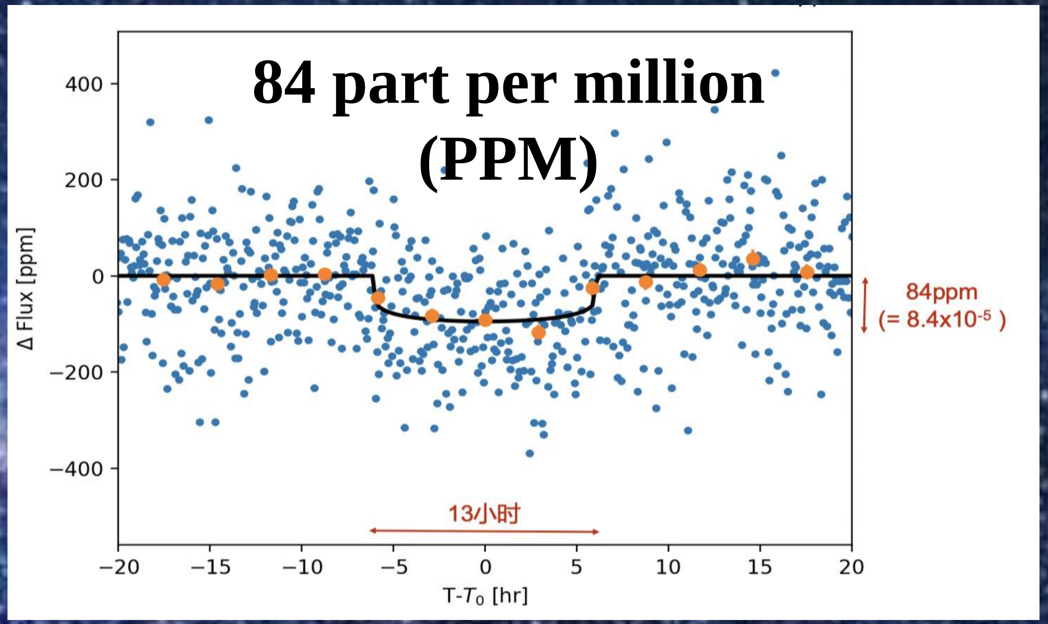


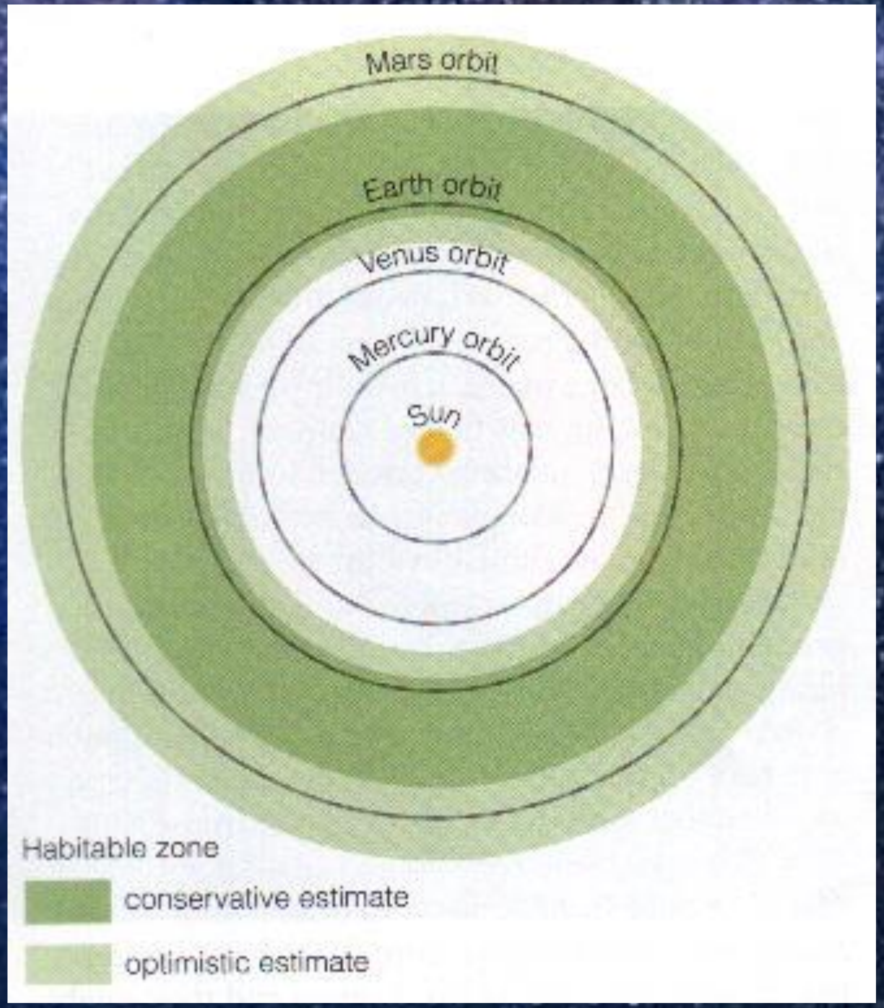


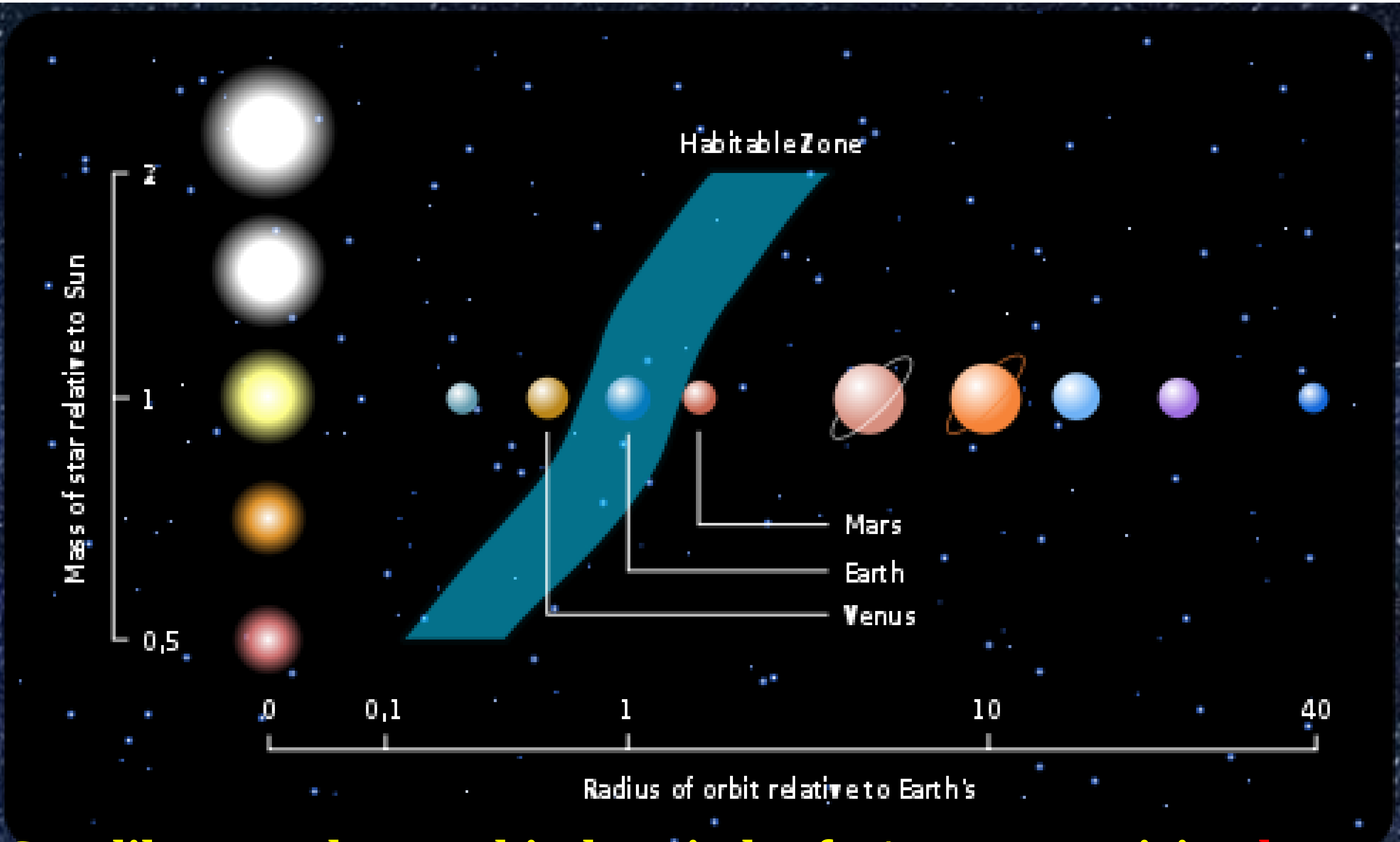
- Earth 2.0's signal very weak, requiring ultra-high precision (~0.1 m/s)
- Stellar activities are major limitations to reach this required precision. The best, ~0.3 m/s achieved by ESPRESSO on VLT , challenging for searching for Earth2.0s, but OK for confirming transit signals with known periods
- Inefficient for searching for Earth 2.0s as a single object instrument, requiring over 400 measurements for detecting multi-planetary systems

It is very Challenging to Detect Habitable Earth-like Planets (Earth 2.0s)

Simulate Earth2.0 Transit Signal

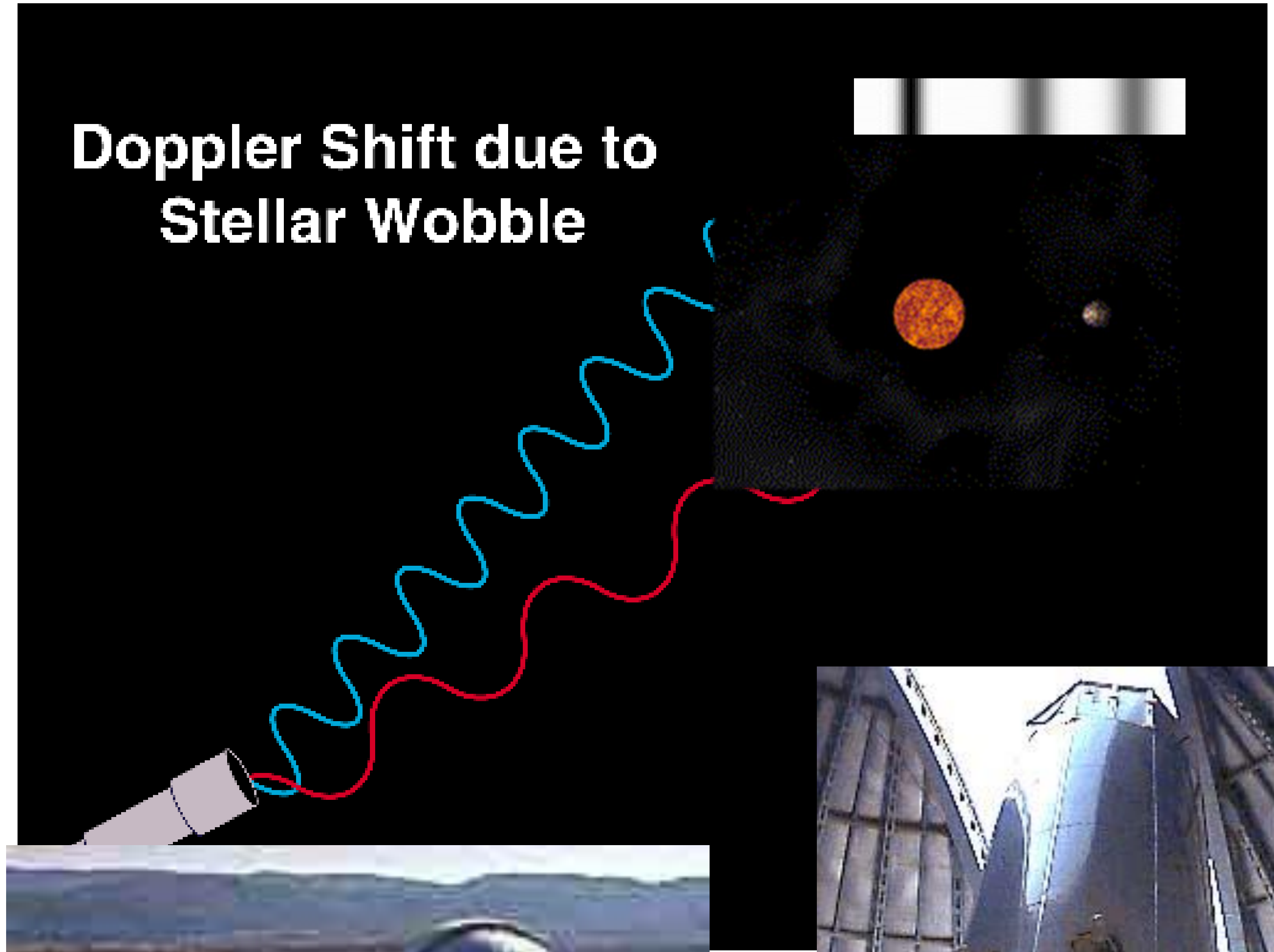


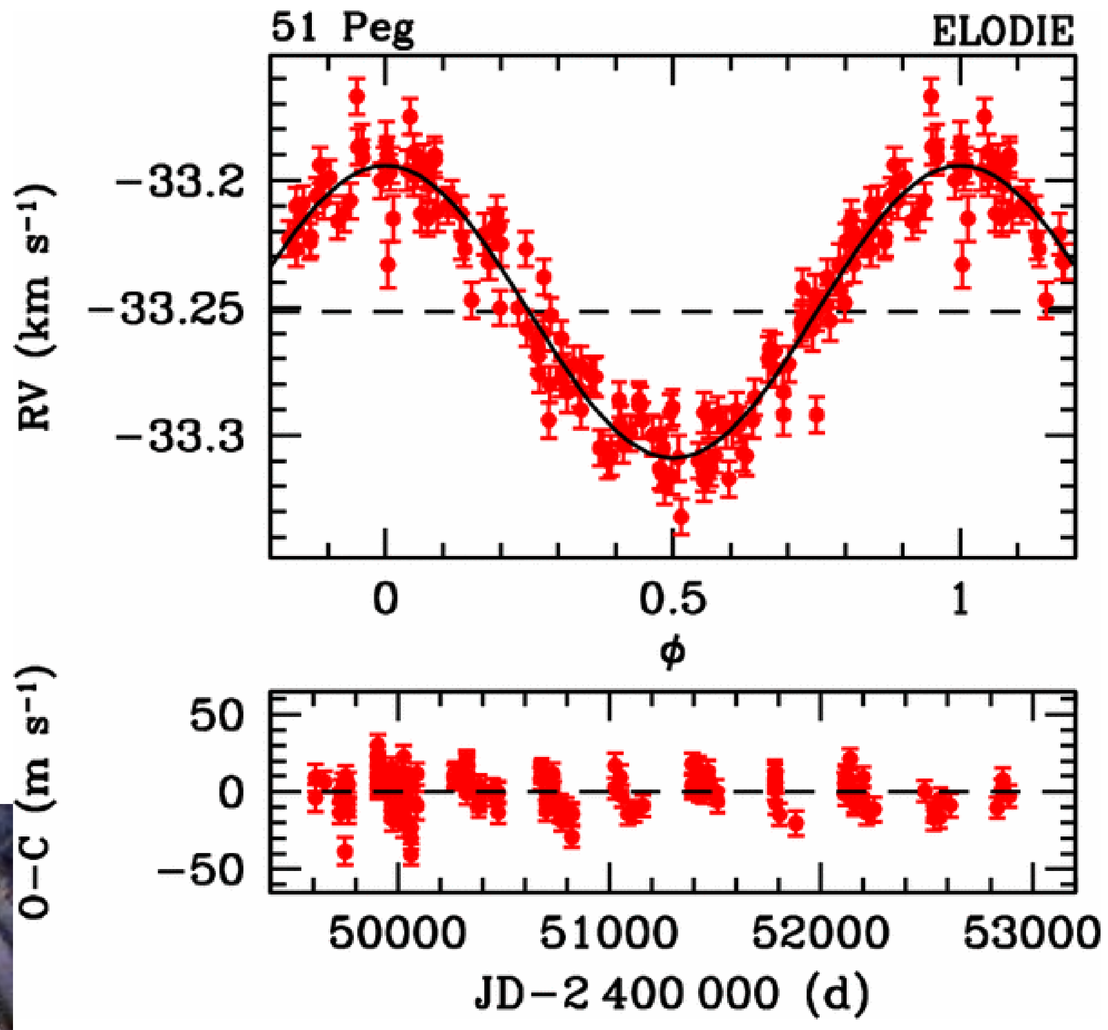




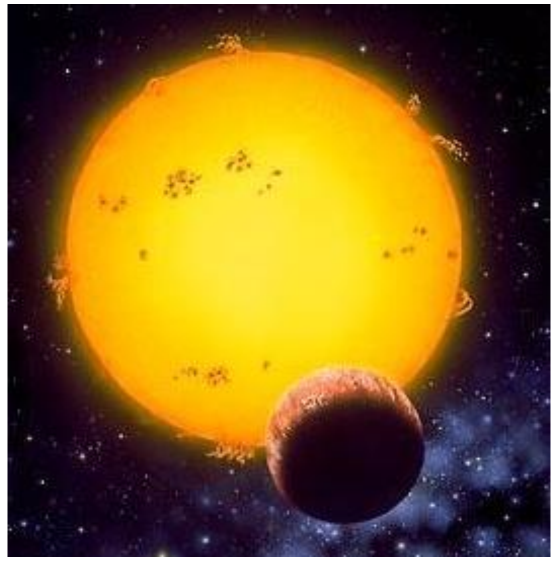
- **Sun-like stars have orbital periods of ~1 year, requiring long-term monitoring**
- **RV signals are very small (~0.1m/s), requiring ultra-high precision (~0.1 m/s) Doppler measurements**
- **Transit signals are extremely weak (84 ppm), requiring ultra-high photometry precision (~34 ppm)**

Doppler Method for Detecting Exoplanets





51Peg



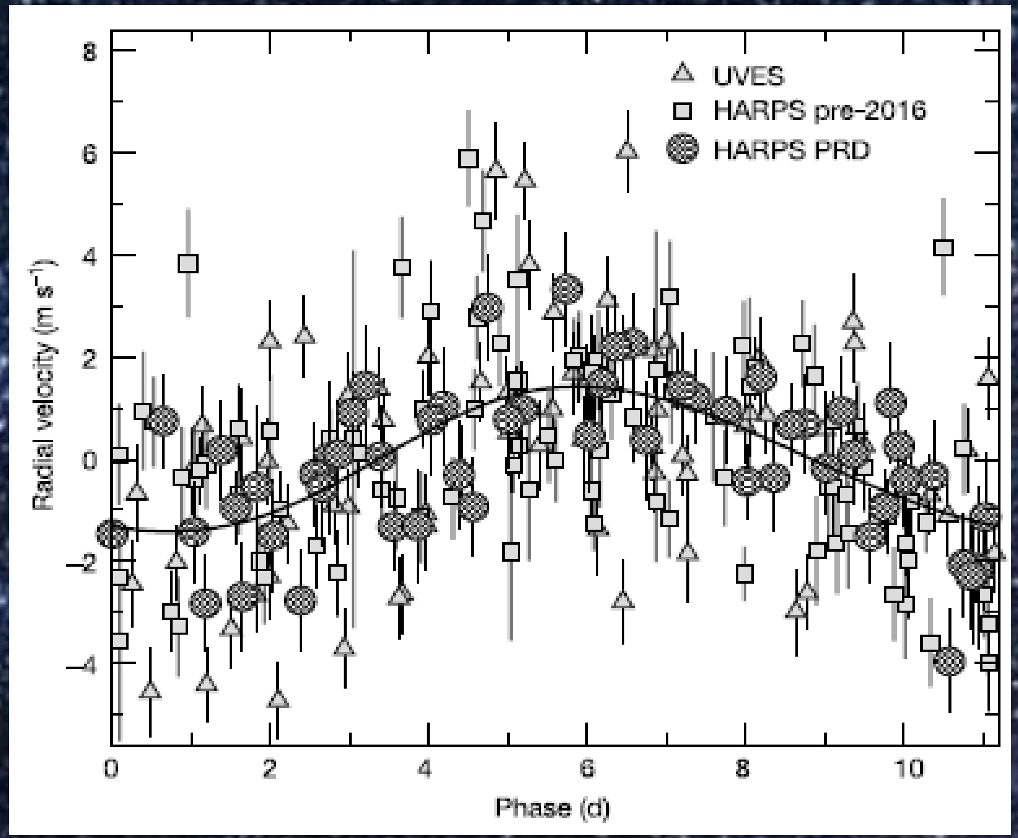
A 0.5 Jupiter mass planet with a 4-day period

The 1.93 meter telescope at the Haute-Provence observatory with a high-resolution optical spectrograph

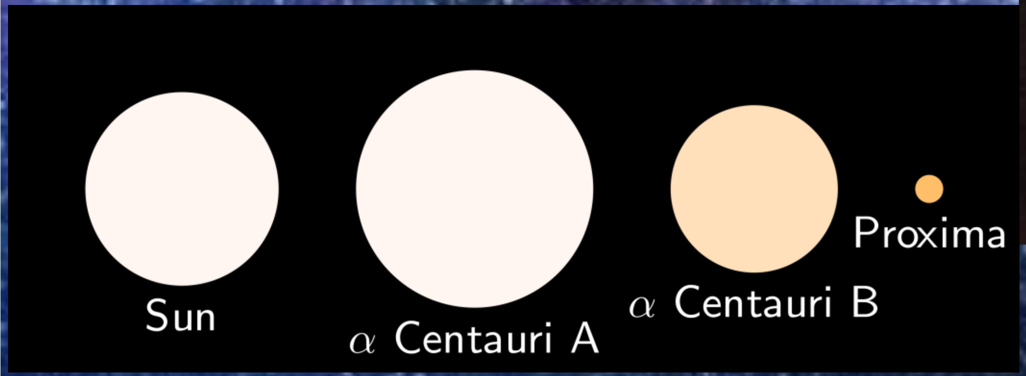
A Potential Habitable 1.3 Earth-mass planet with a Period of 11.2 days orbiting Proxima Centauri (0.12 solar Mass, 4.2 light years)

Anglada-Escude Guillem et al. 2016, Nature

Radial Velocities



PRD: Pale Red Dot

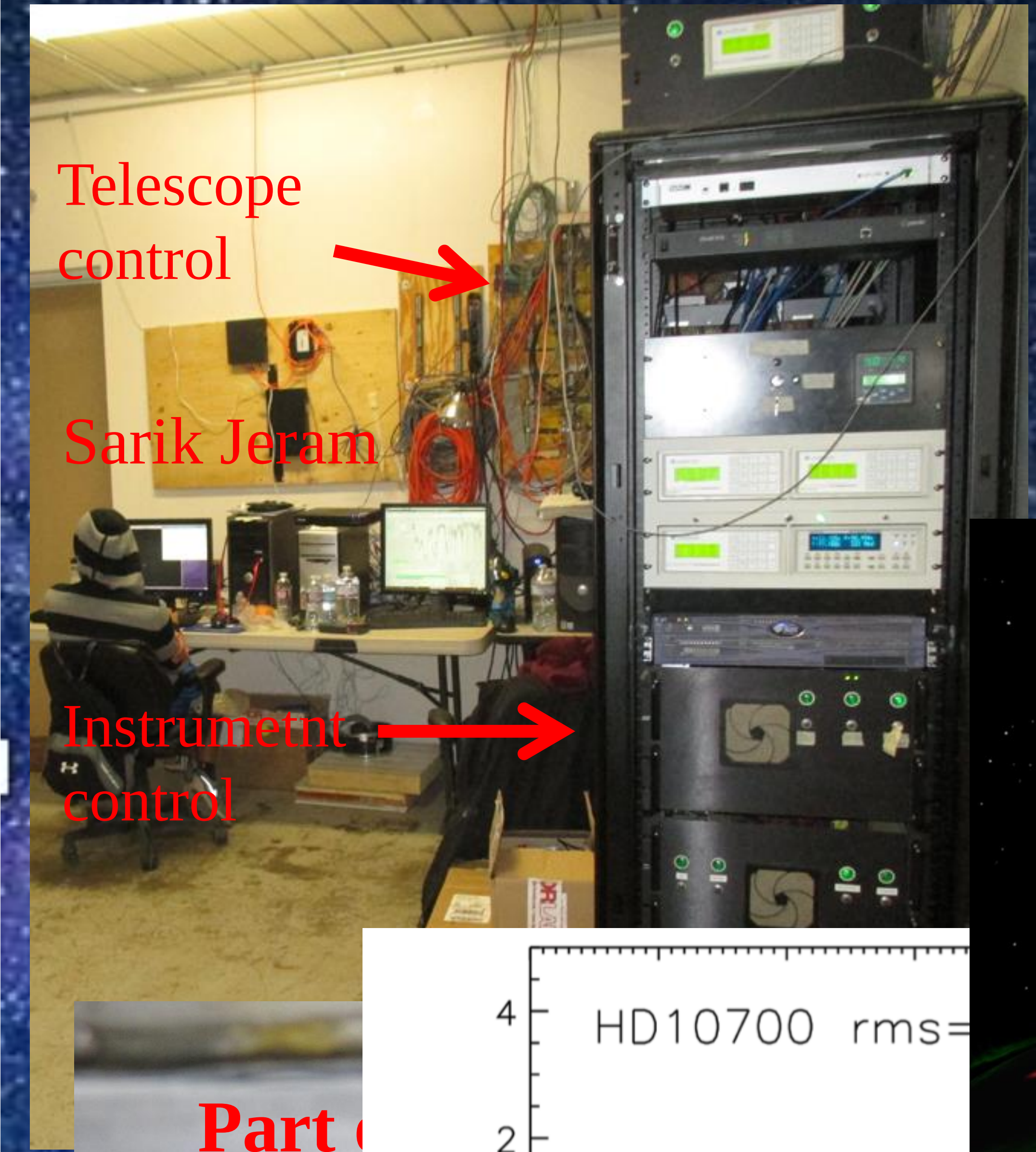


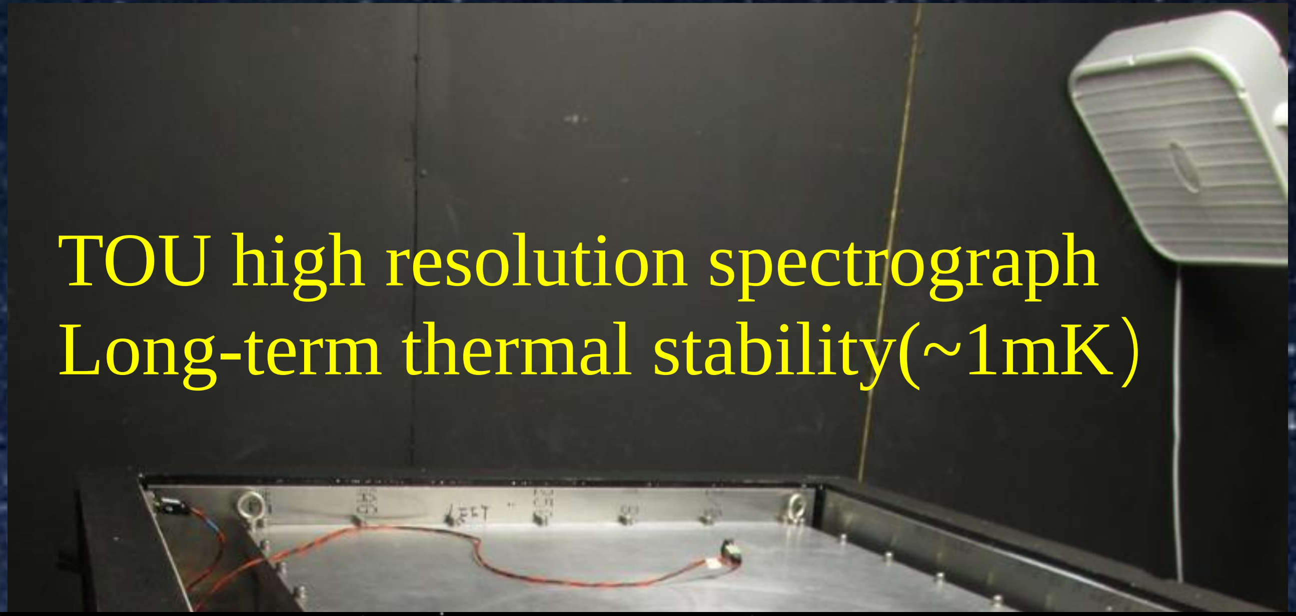
https://en.wikipedia.org/wiki/Alpha_Centauri

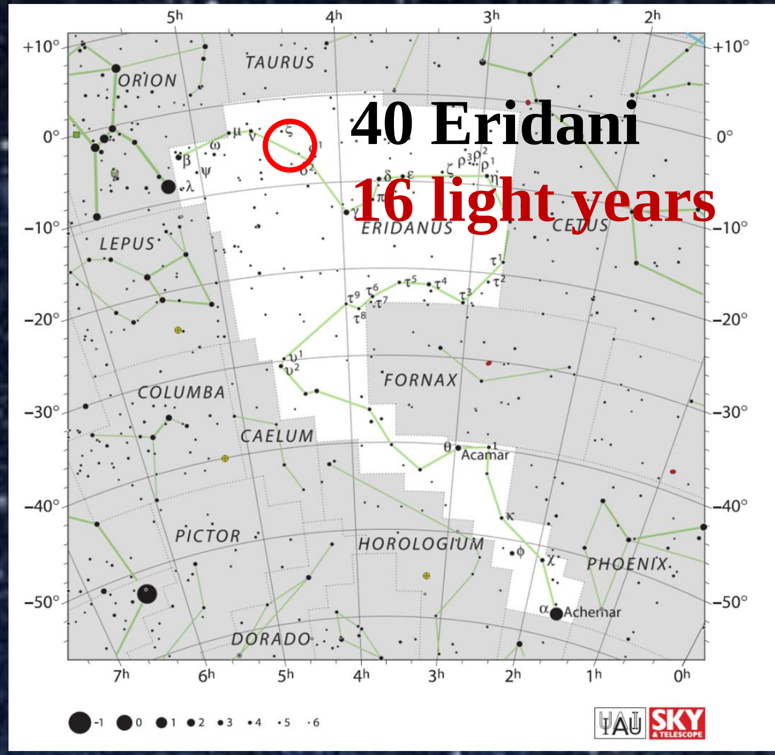
Nature's 10
Ten people who mattered this year.

http://www.nature.com/news/nature-s-10-1.21157

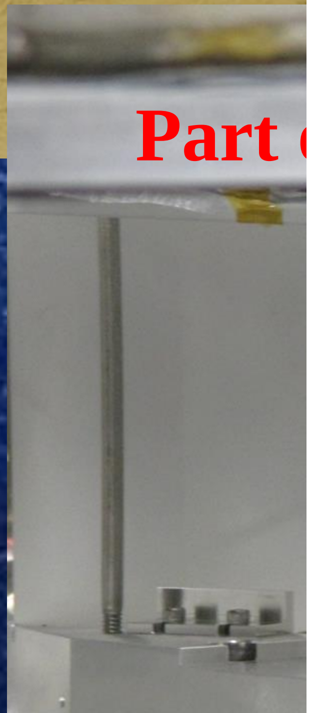
Dharma Planet Survey of nearby solar type stars for low-mass planets

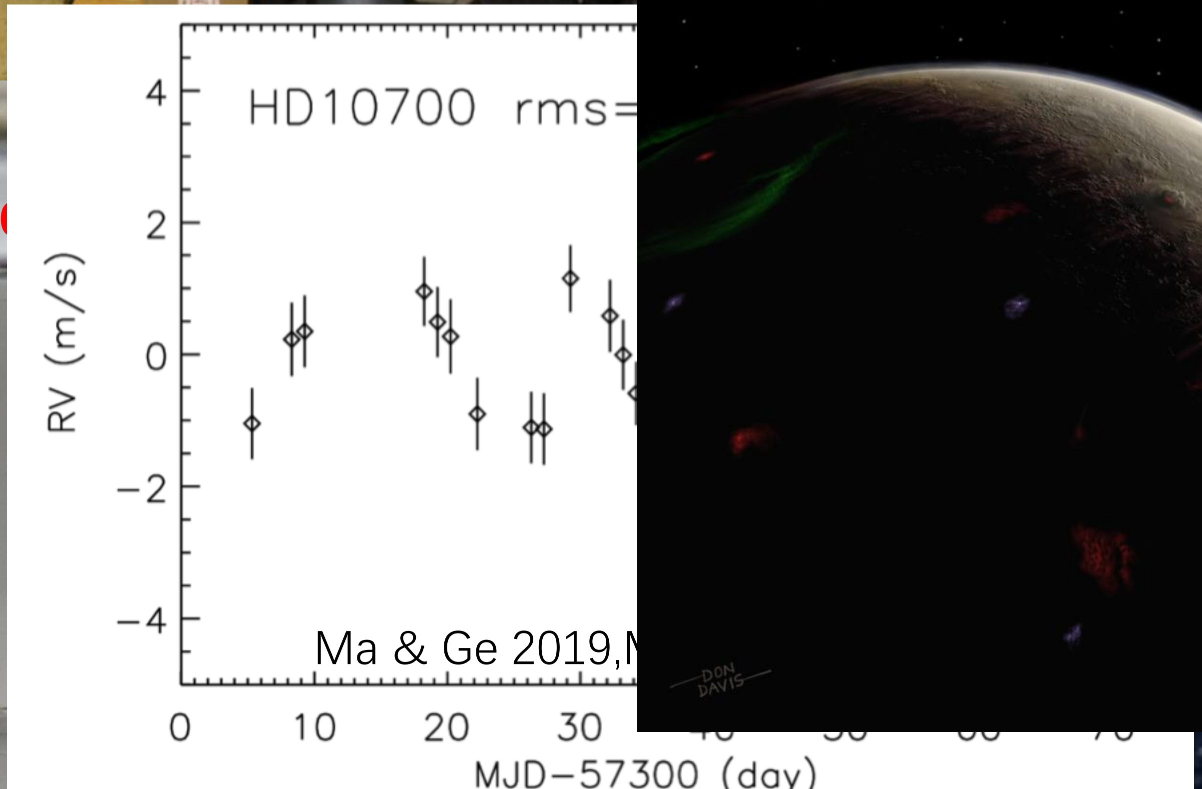


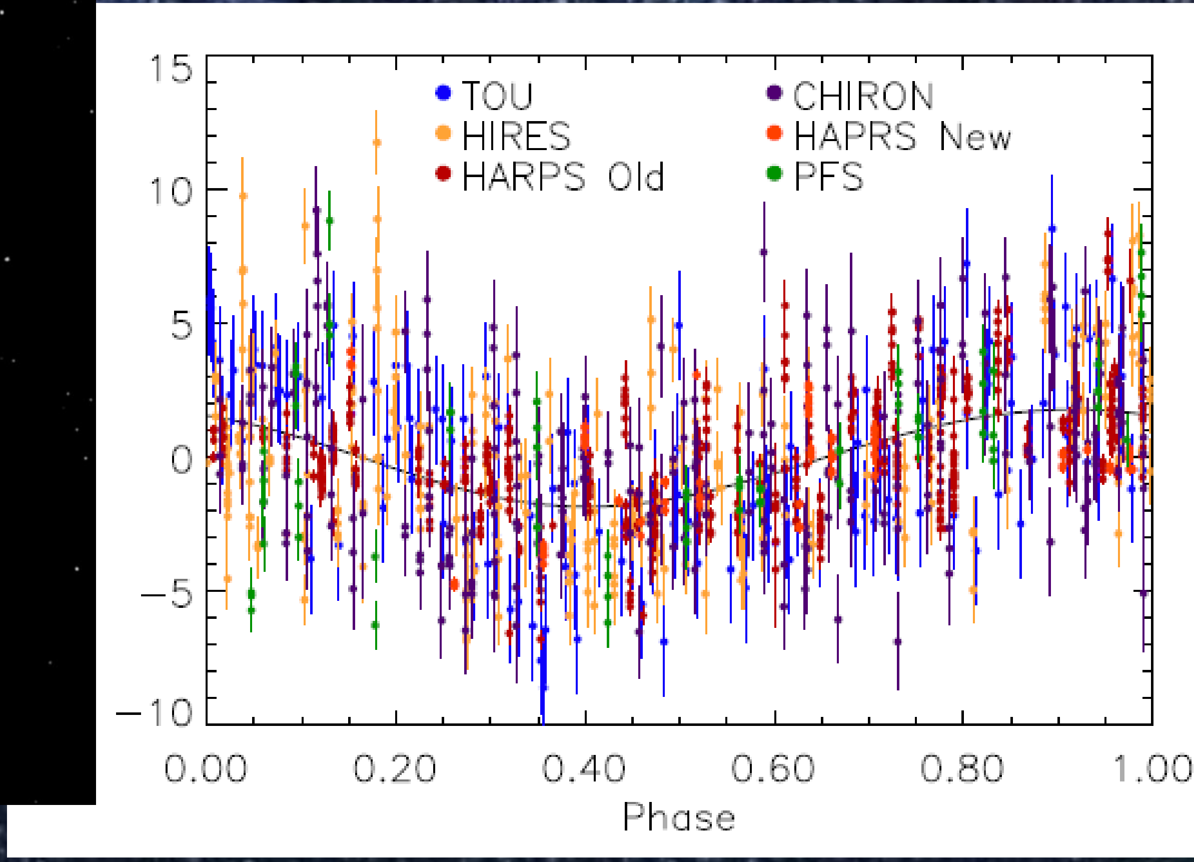




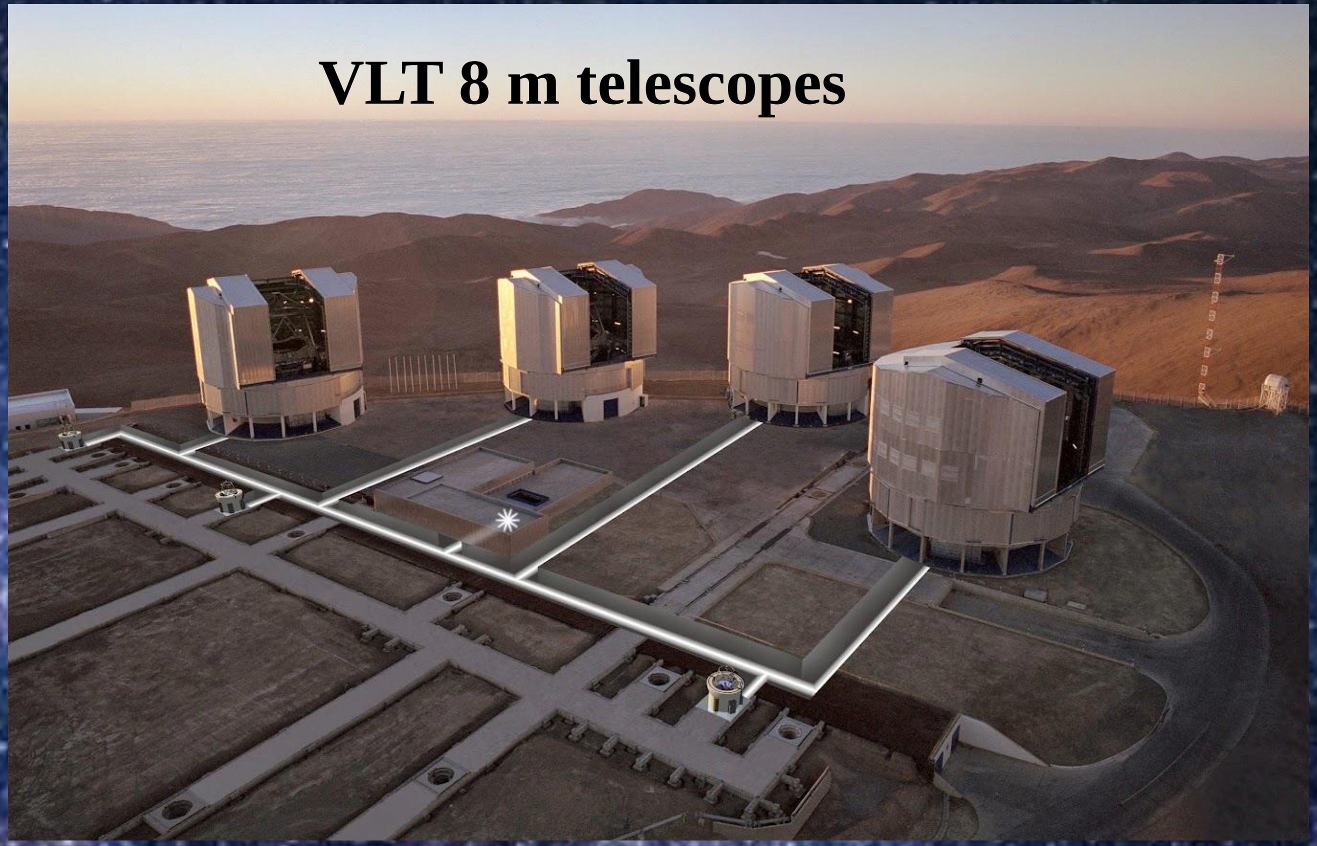
ulcan planet around 40 Eridani,
Isini = 8.5±0.5 M$_\oplus$
= 42.38±001 d

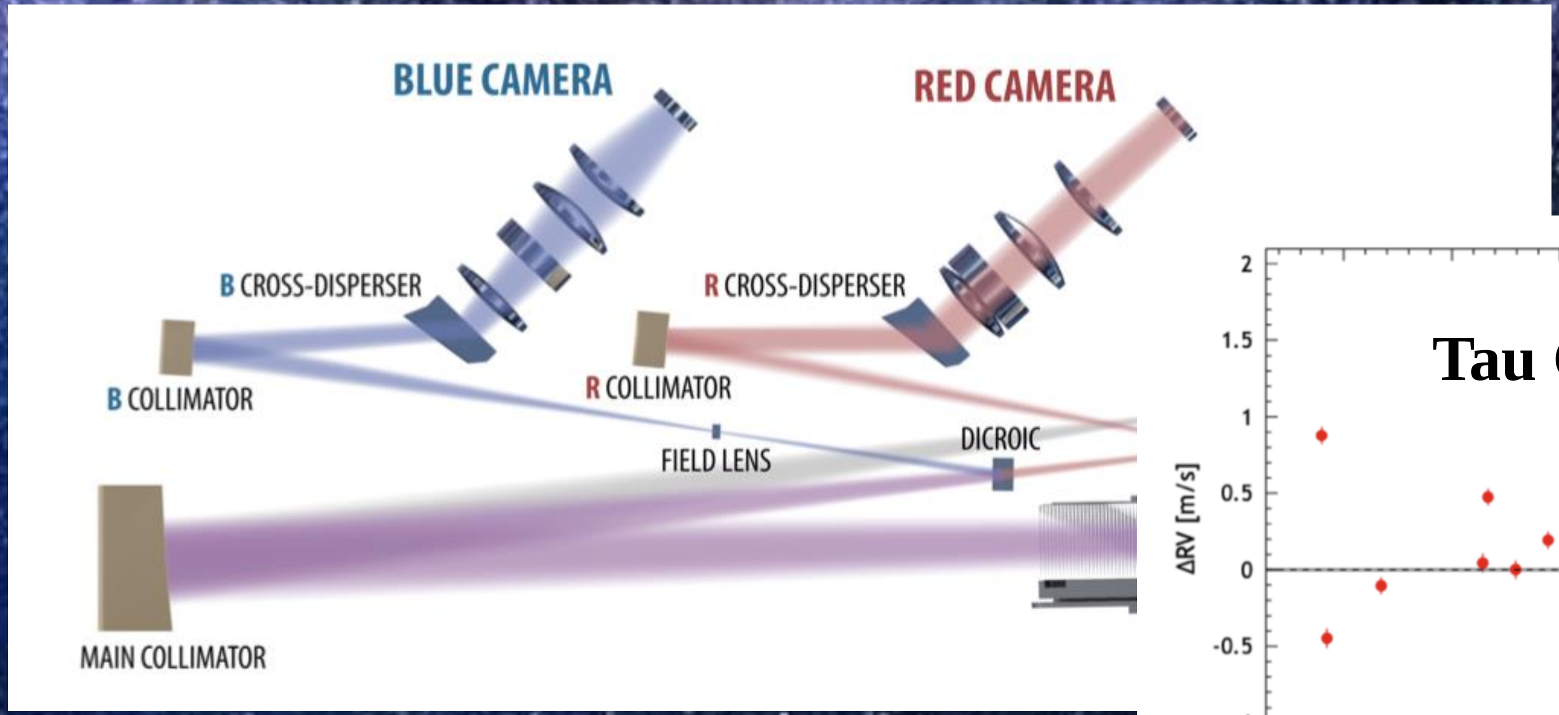


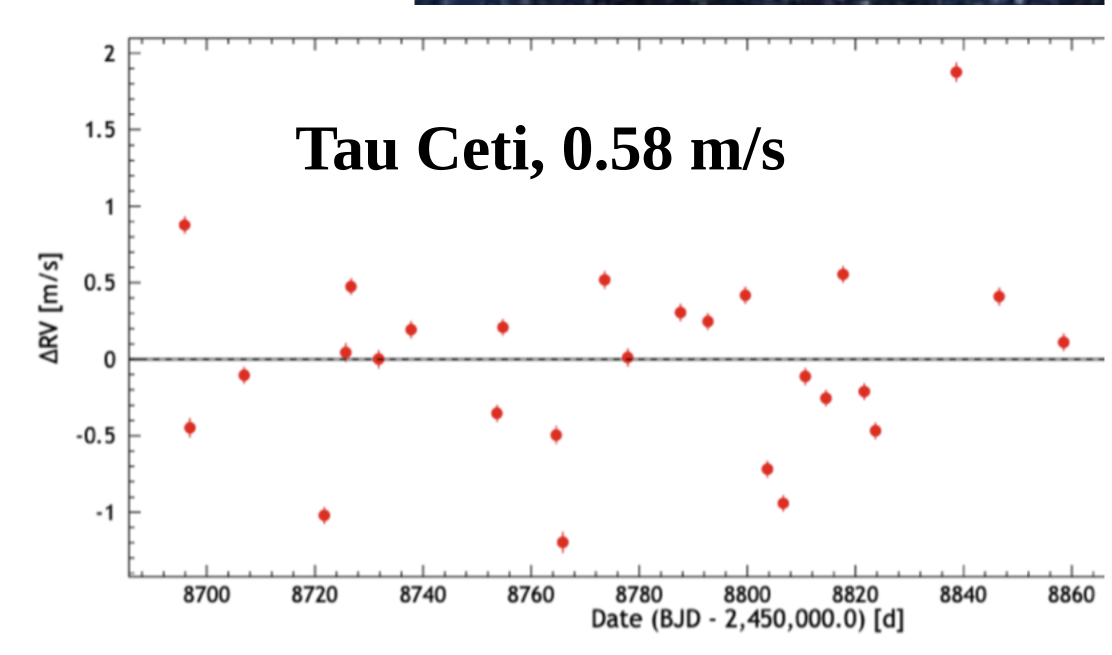


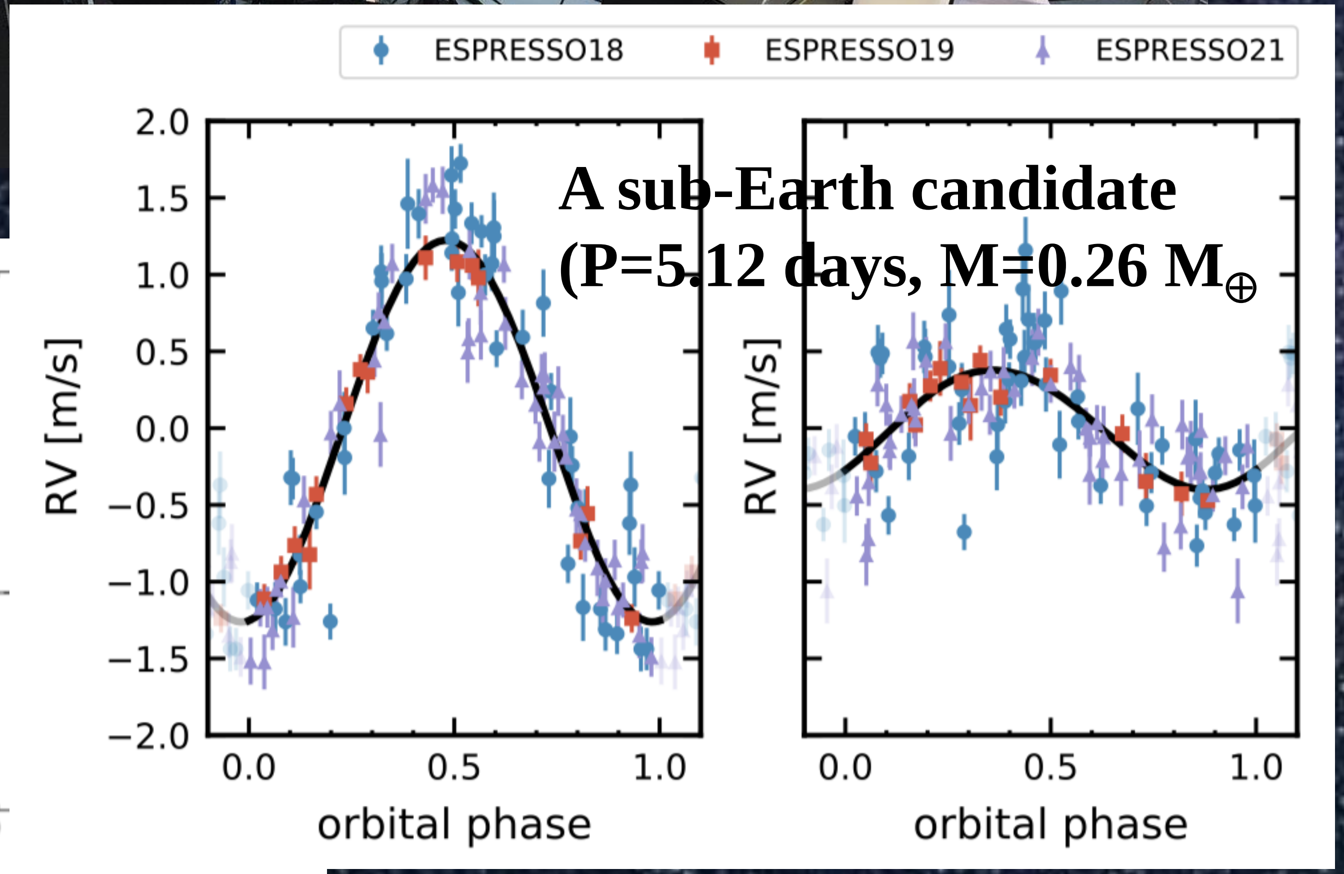


New state-of-the-art high precision Doppler spectrograph: ESPRESSO



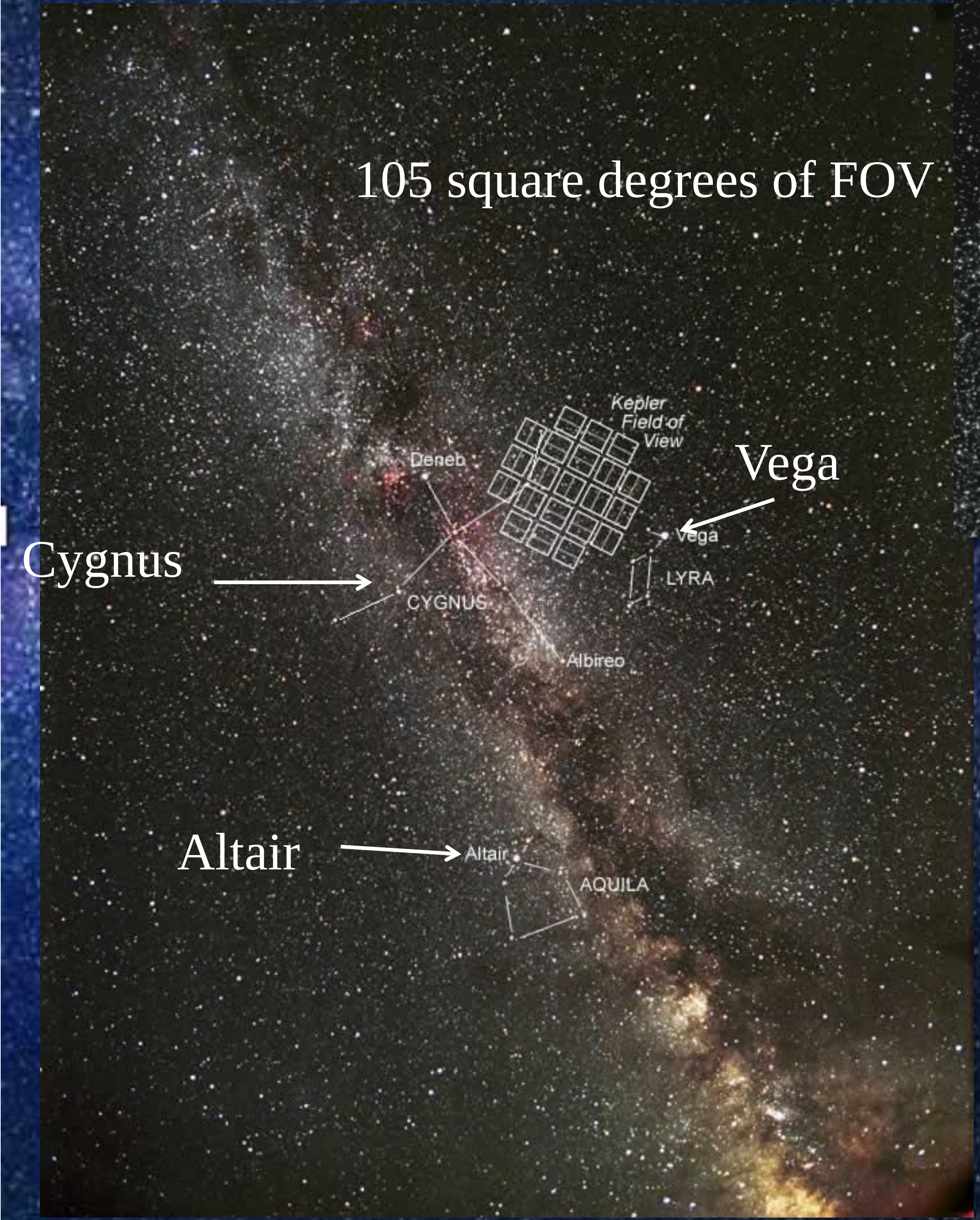






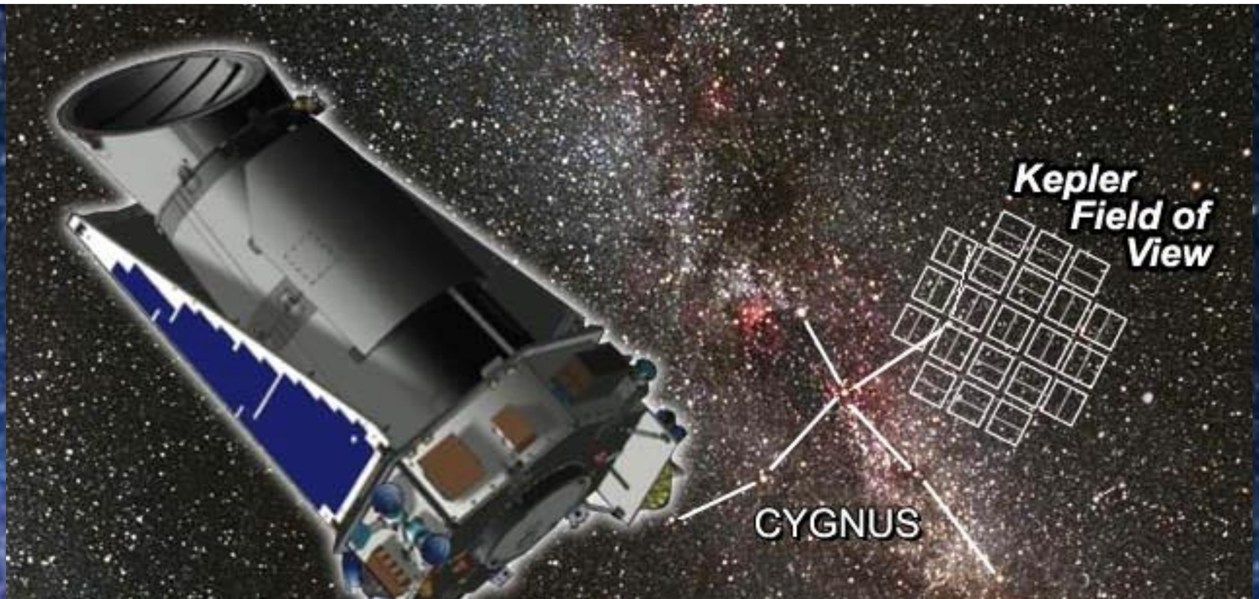
Pepe et al. 2021; Faria et al. 2022

NASA Kepler Space Mission (2009-2018)

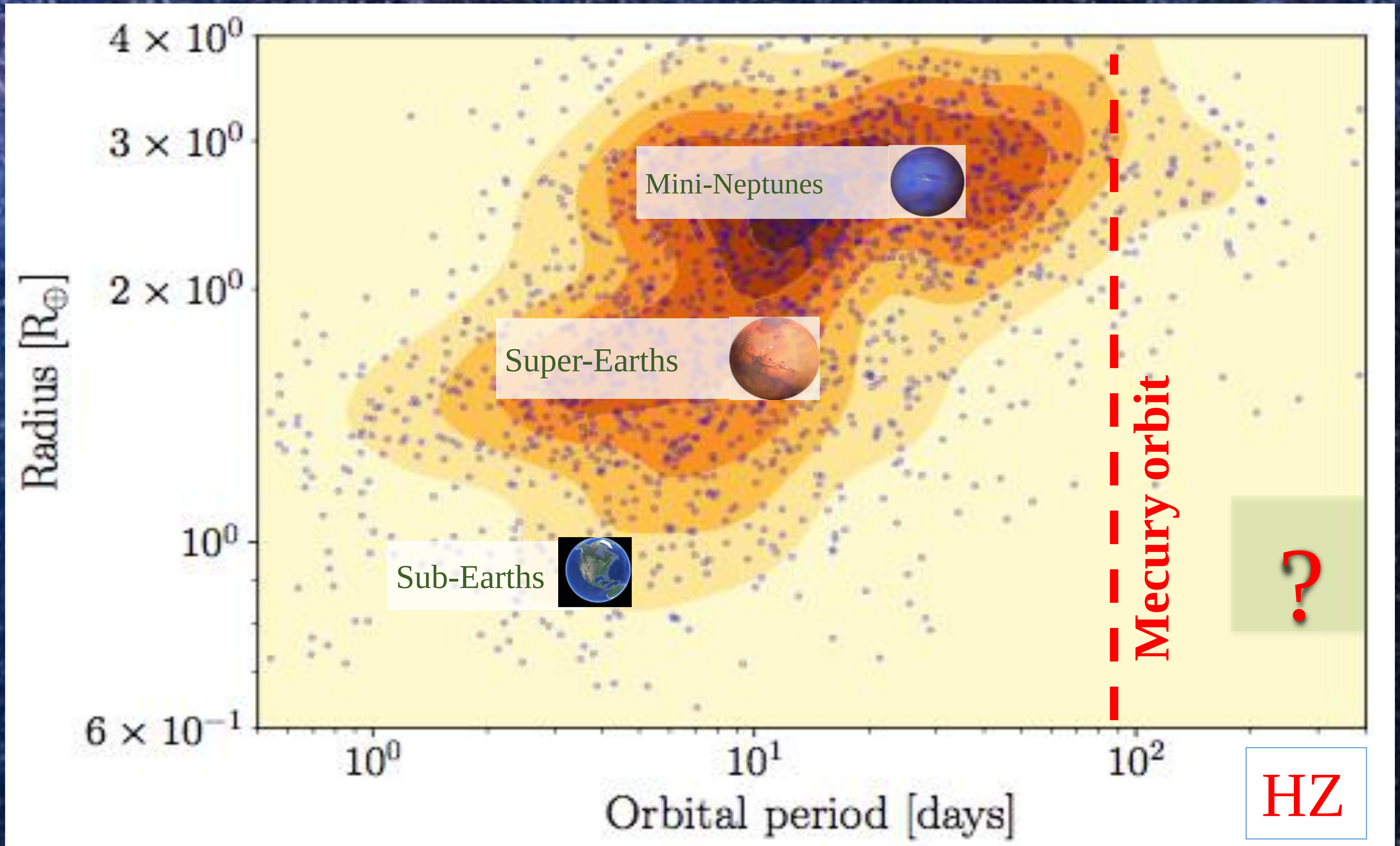


- 0.95 meter wide field telescope to monitor the same sky field for 4 years to detect transiting planets including habitable Earth-like planets around solar type stars.

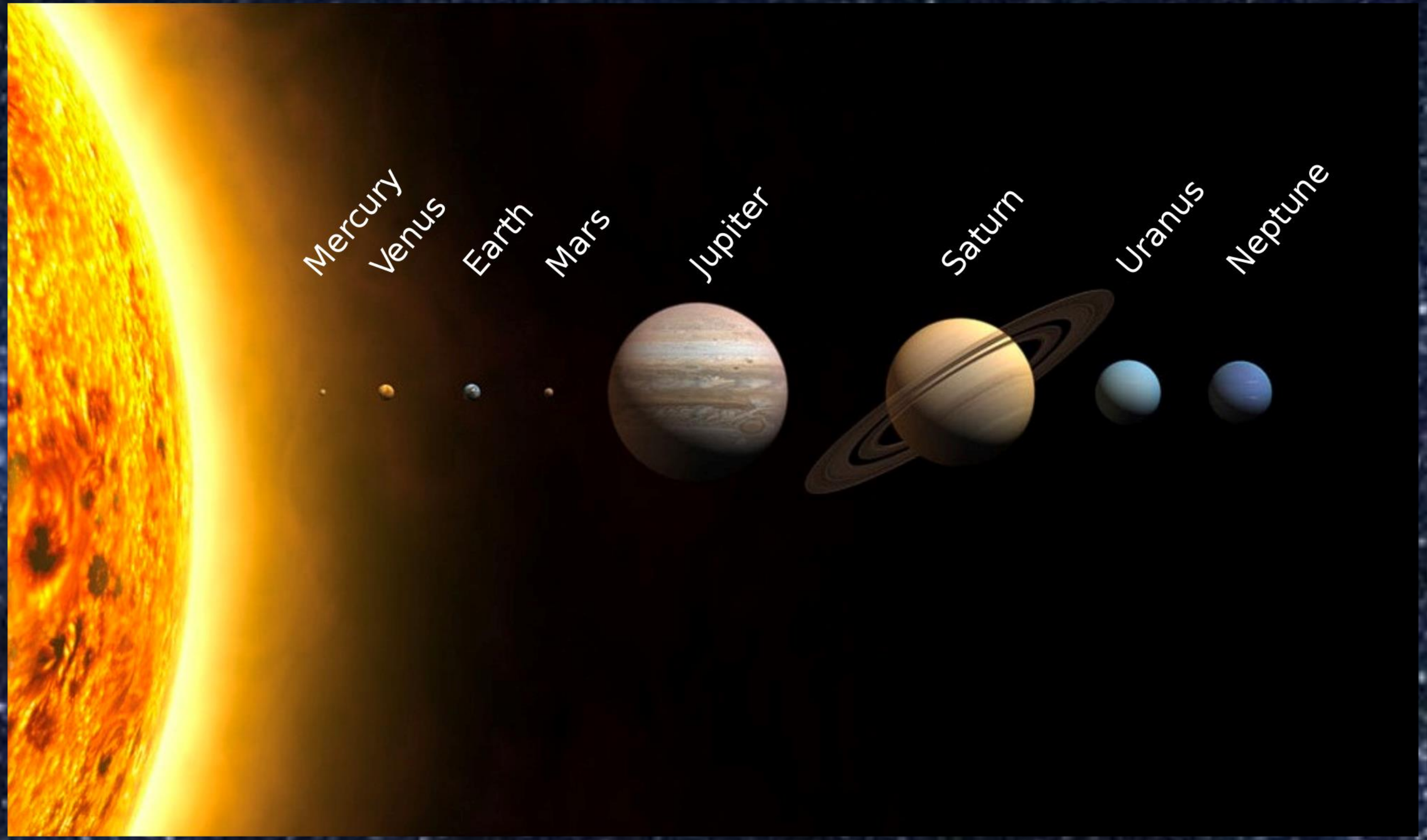
Kepler Space Mission (2009-2013, NASA)



- **FOV: 105 square degrees**
- **Observe 170,000 FGKM dwarfs for 4 years**



- One of the main science objectives： to search for habitable Earth-like planets orbiting sun-like stars (Earth 2.0s) and determine its occurrence rate.

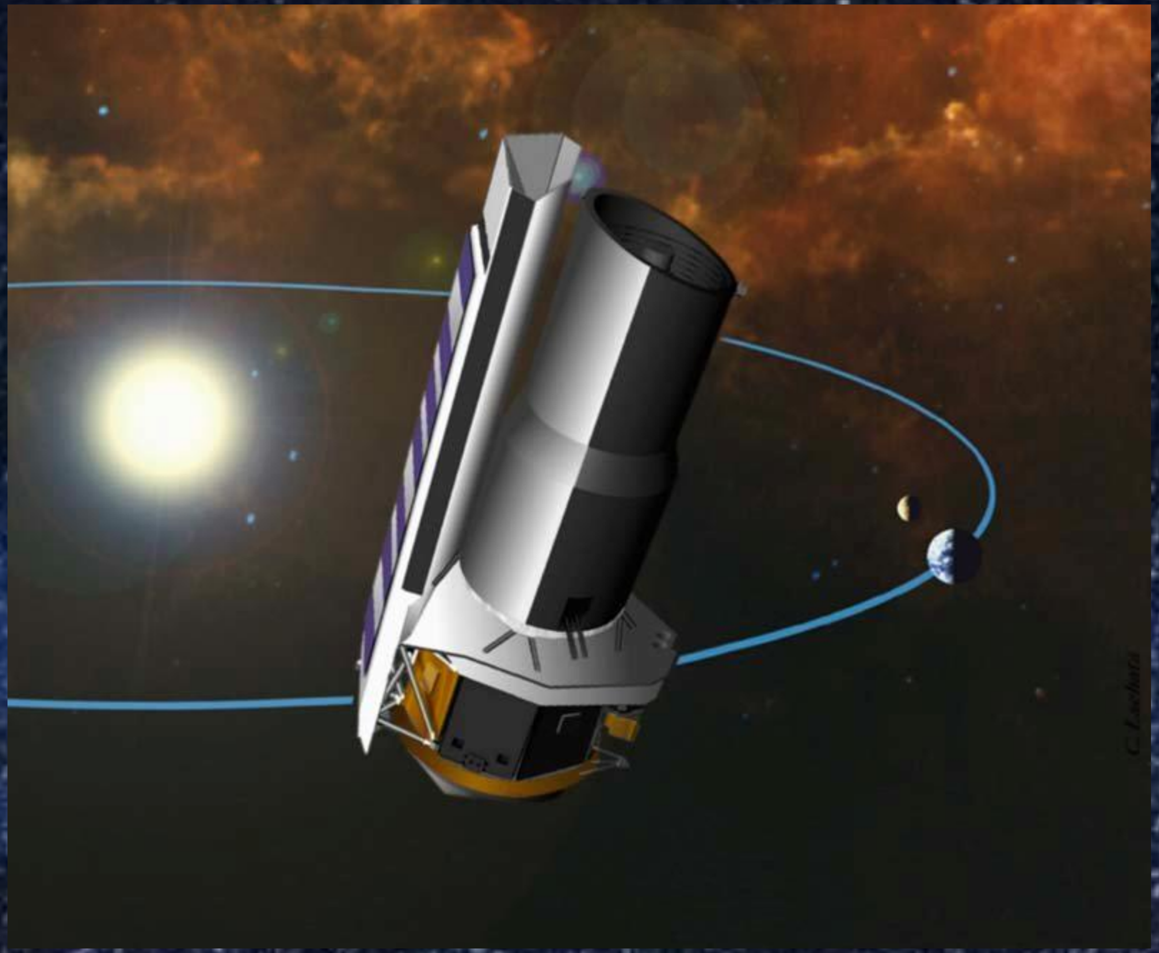


- Discovery of Close-in super-Earths and sub-Neptunes are the dominant planet populations around FGK dwarfs
- Kepler has not detected Earth 2.0s due to its relatively small FOV, small number of quiet sun-like stars, high readout noises and failure of reaction wheels at the end of the 4^{th} year of operation.

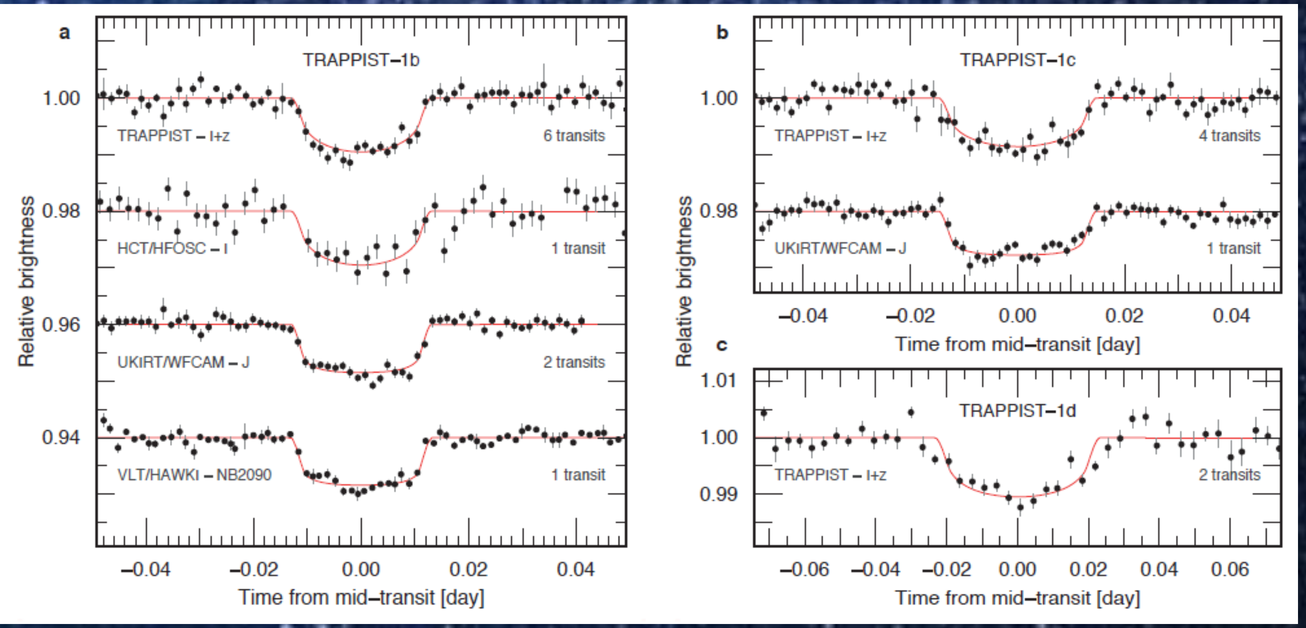
Three transiting habitable Earth-size planets orbiting a M Dwarf, Trappist-1

60cm TRAPPIST telescope in Chile

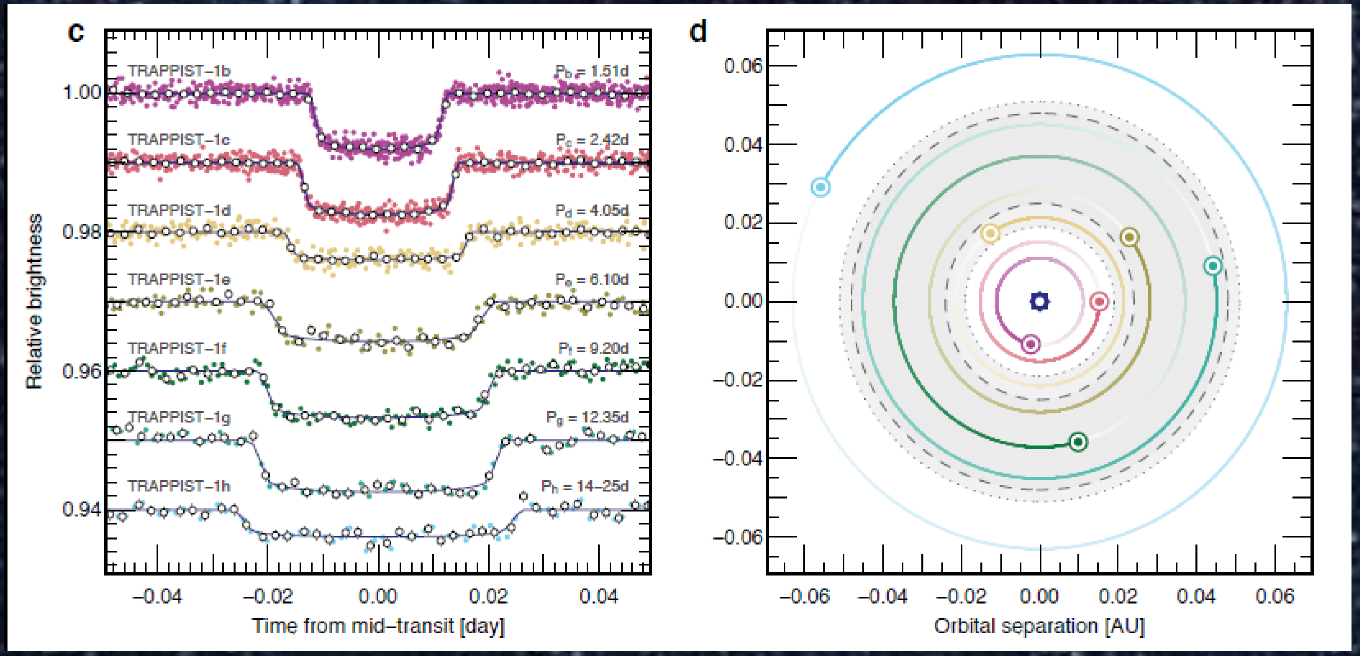
NASA 85cm Spitzer space telescope



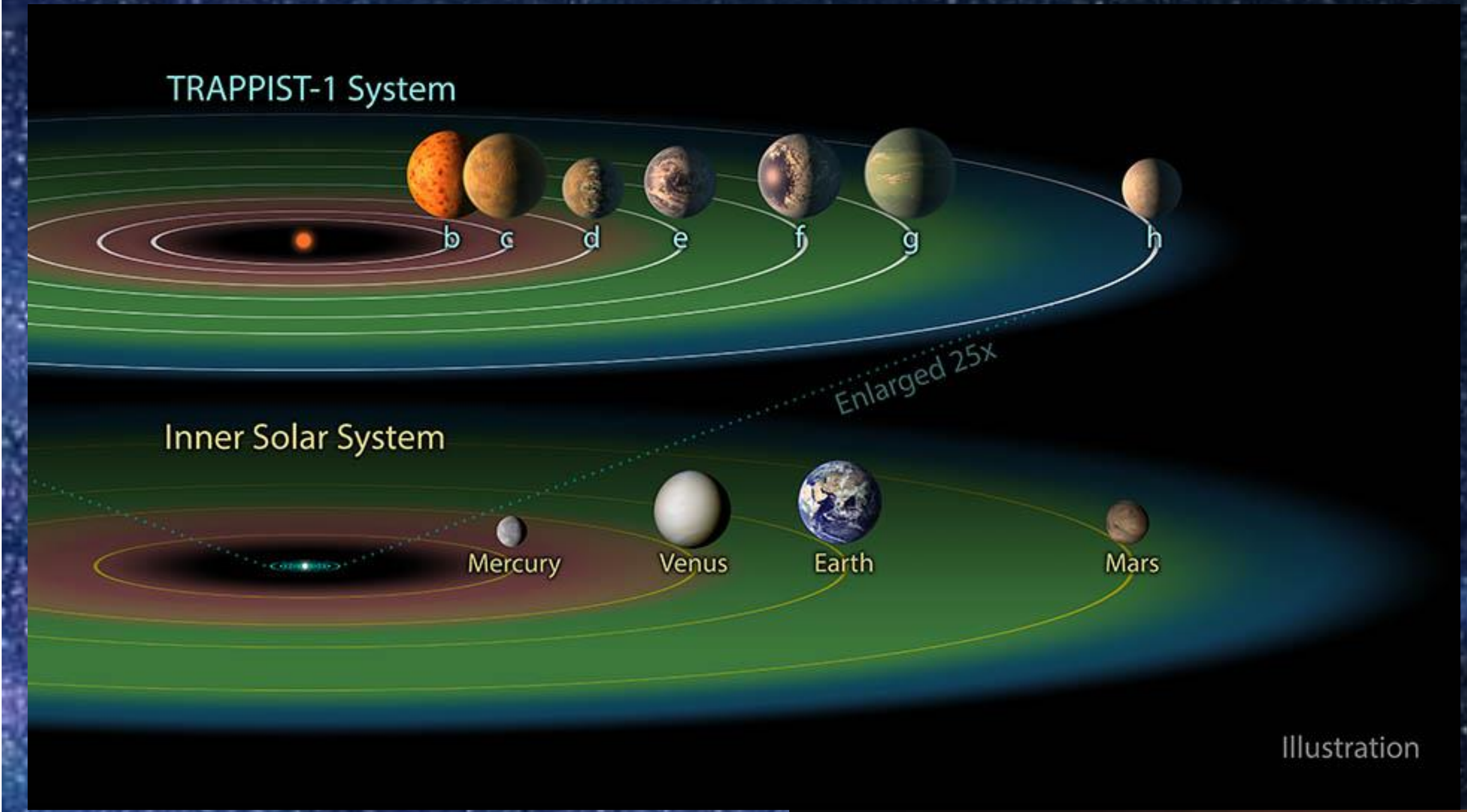
Trappist-1 light curves with the Trappist telescope



Trappist-1 space photometry data



Three habitable Earth-size planets orbiting the M Dwarf, Trappist-1 (0.08 solar mass, ~41 light years) (Gillon et al. 2017)

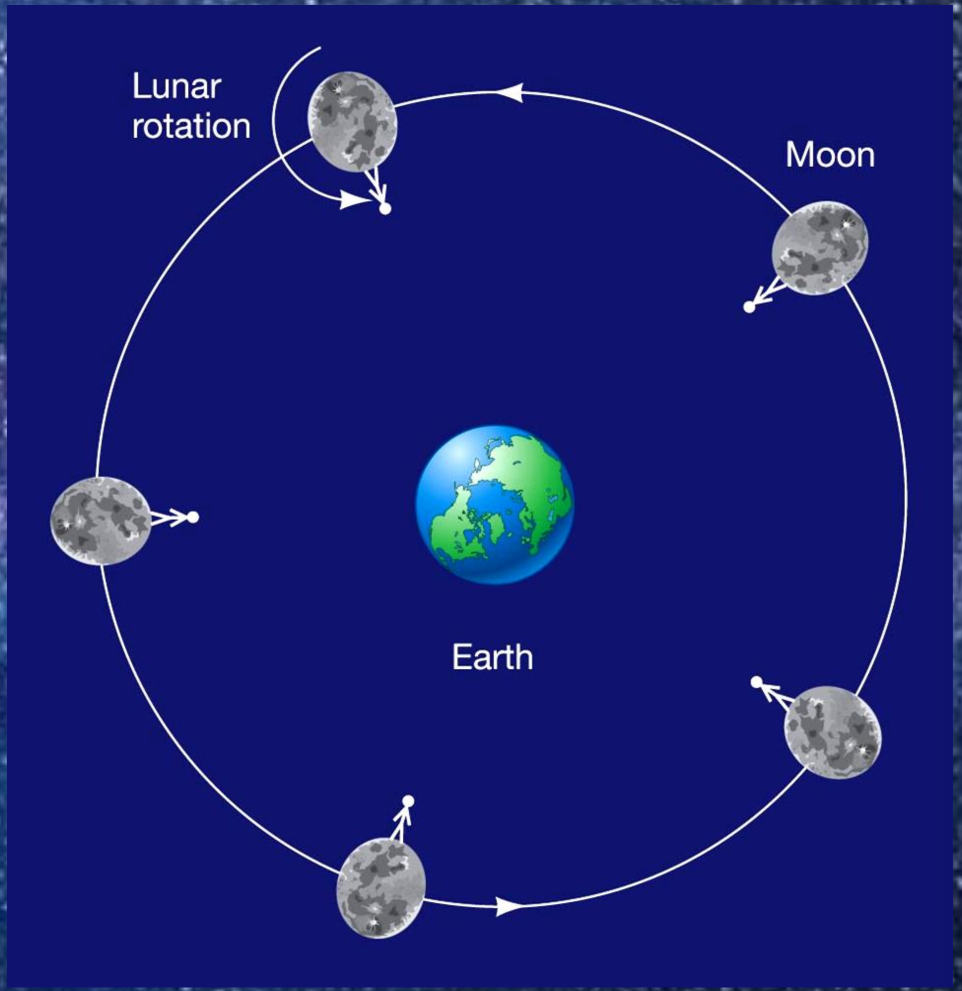


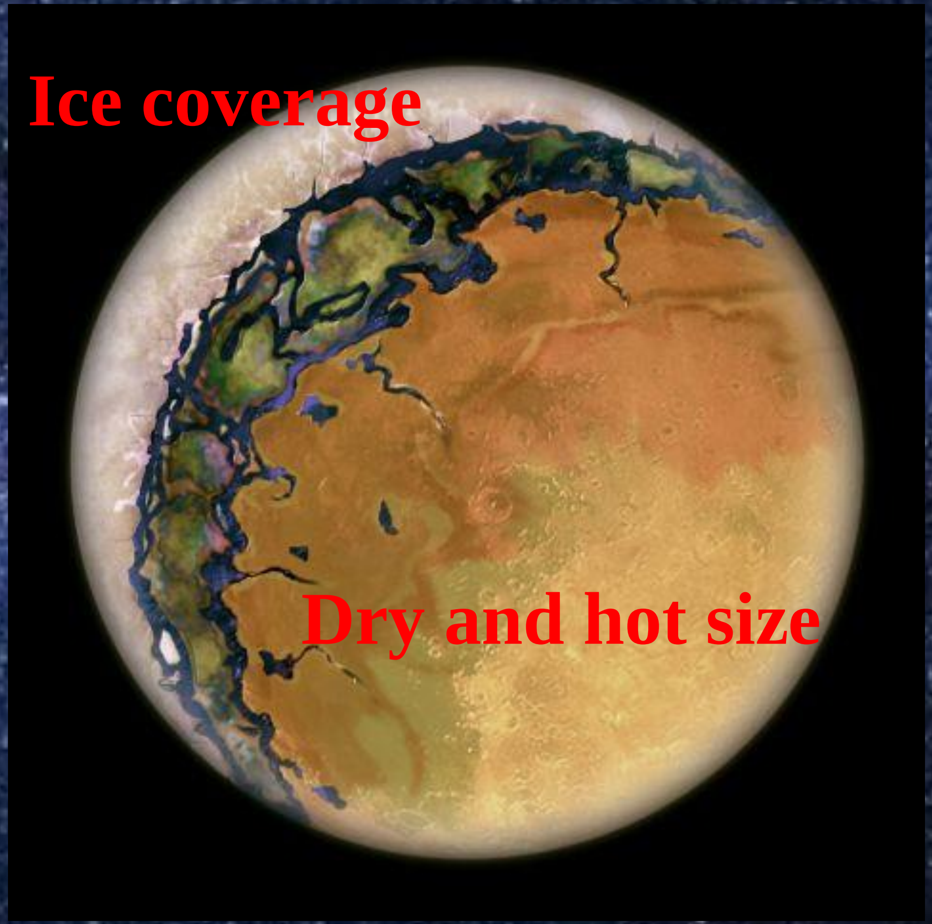
- Trappist-1 e,f,g, 0.69、 1.04 and 1.32 Earth masses habitable planets
- Orbital periods: 6.1. 9.2 and 12.4 days

https://exoplanets.nasa.gov/trappist1/

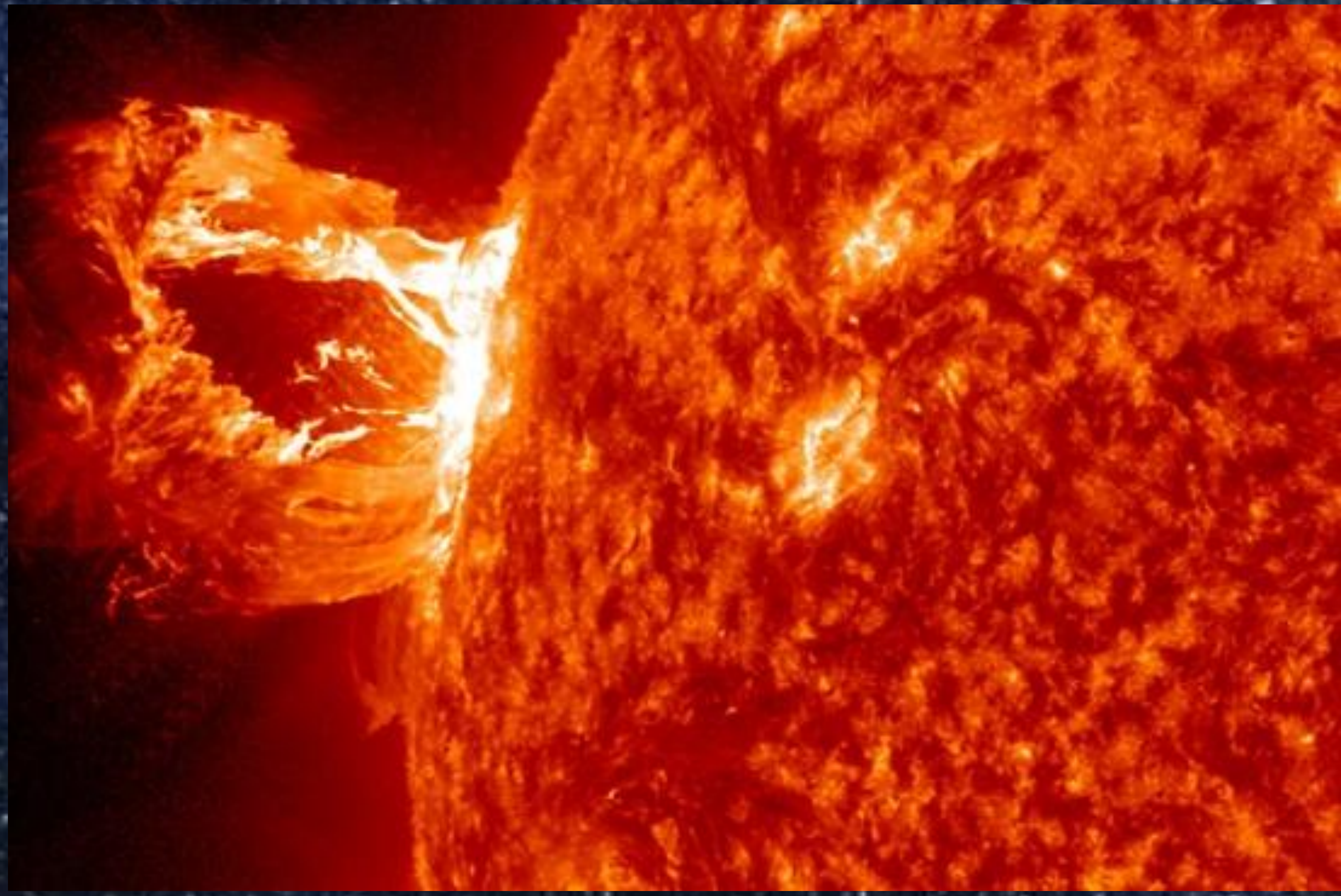
Main challenges for life on habitable planets around low-mass M dwarfs

Tidal locking makes one side dry and hot while the other side possibly covered by ices, which is not hospital to life formation and evolution





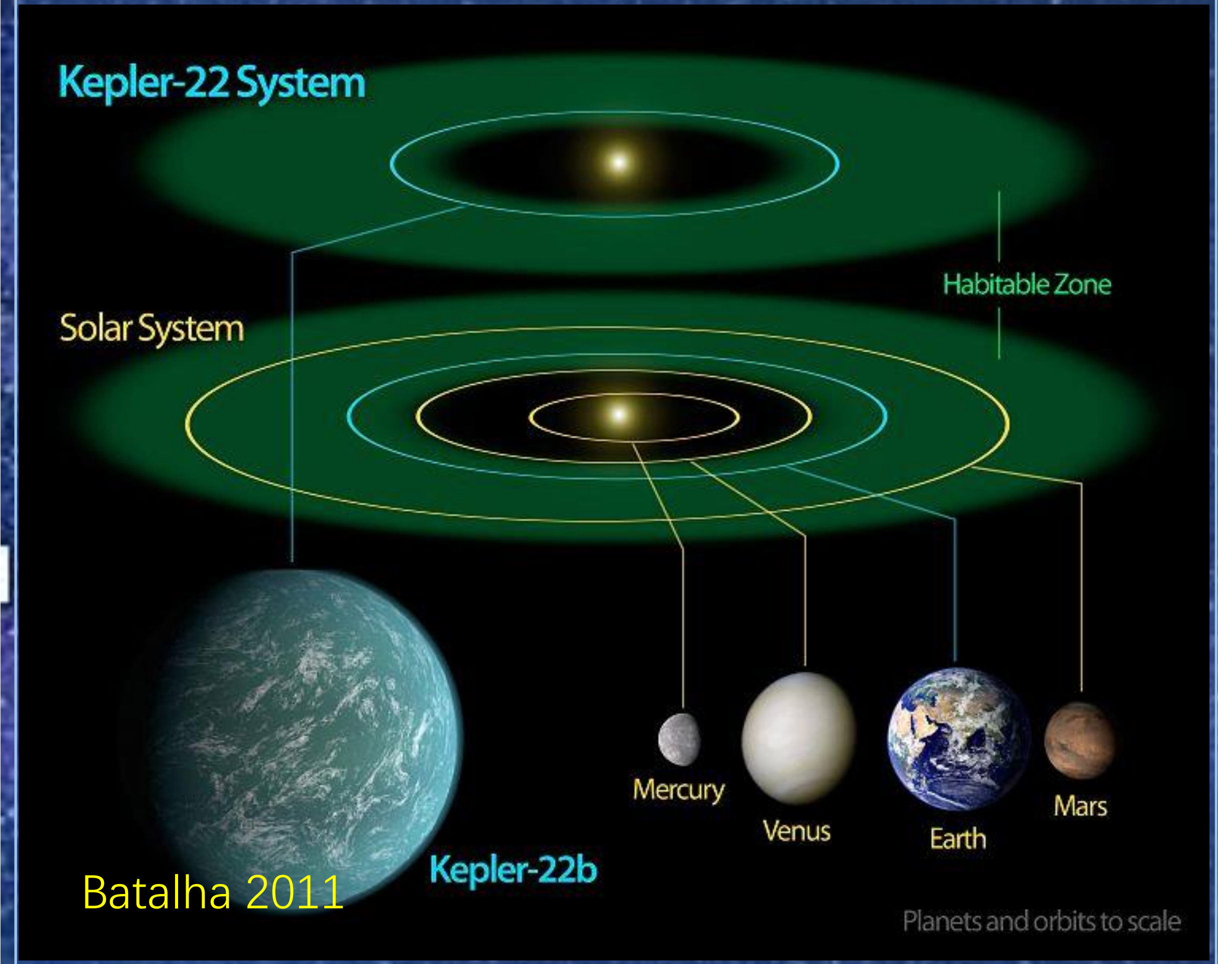
M dwarfs have super flares (including UV) with ~10-1000 times power of the Sun, which may kill all lives



- Habitable environments around M dwarfs are much more extreme than our solar system
- Peak of the M dwarf radiation is at ~1 μm （Sun at 0.5 μm)， life would be very different from Earth if existing

Habitable planet candidates around solar type stars discovered by Kepler

Kepler-22b



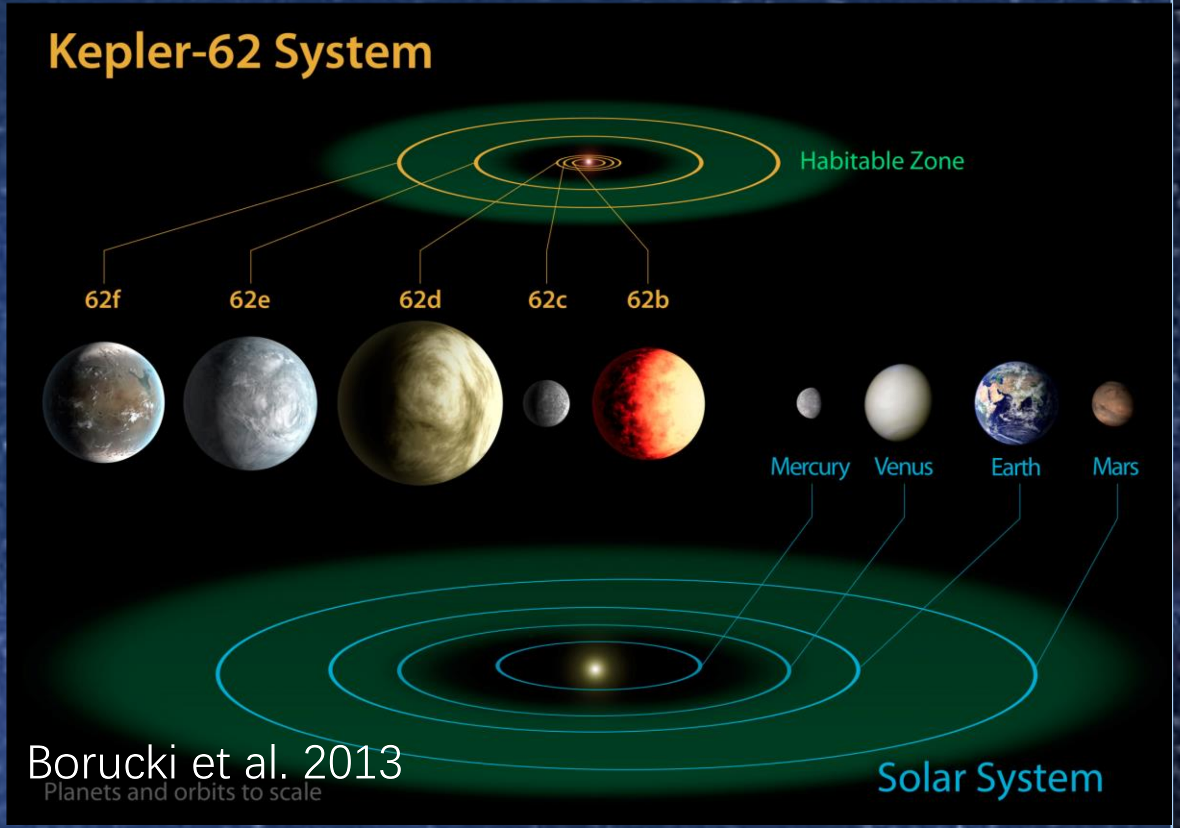
•Host star: 0.97 solar mass, ~600 lys

Habitable planet:

•P=289.9 days

•R=2.4 $R_{\oplus}$

Kepler62e,f



•Host star: 0.69 solar mass, ~1200 lys

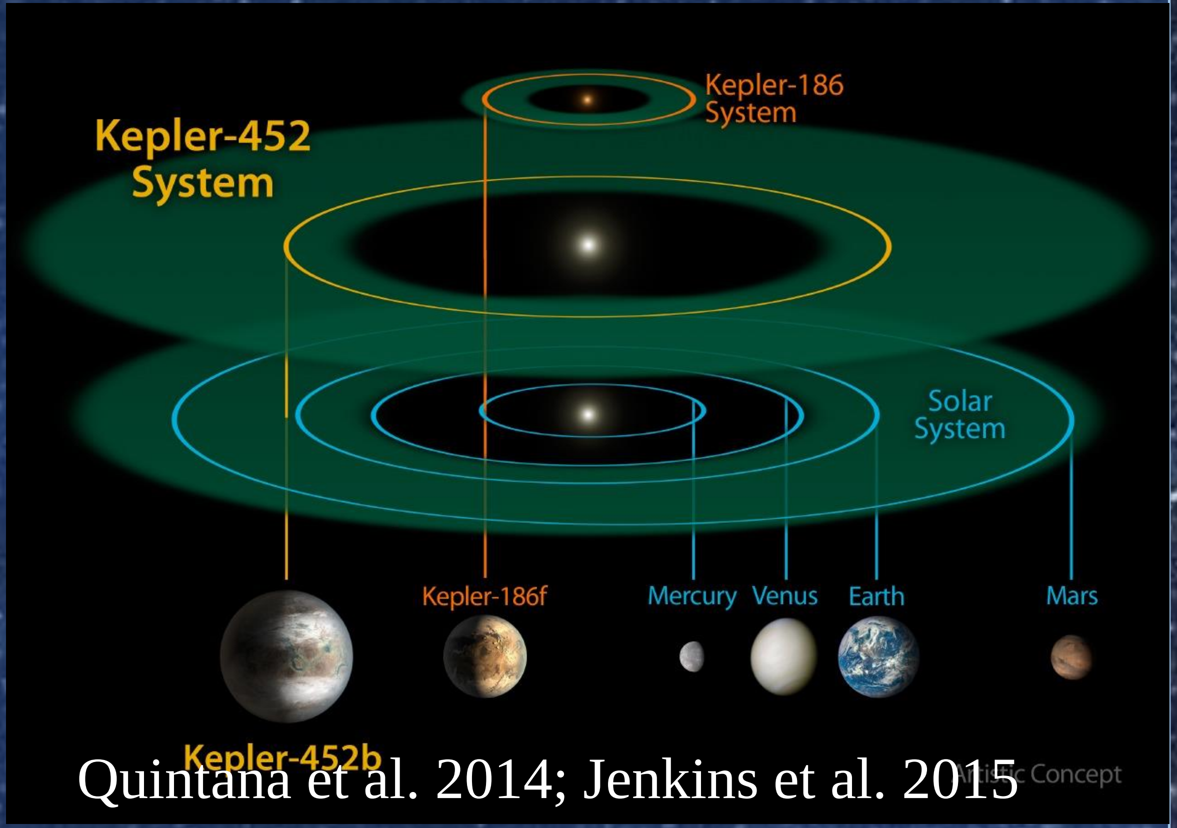
Habitable planet:

•P=122， 267 days

•R=1.6， 1.4 $R_{\oplus}$

•M=4.5， 2.8 $M_{\oplus}$

Kepler-452b



•Host star: 1.04 solar mass, ~1830 lys

Habitable planet:

•P=385 days

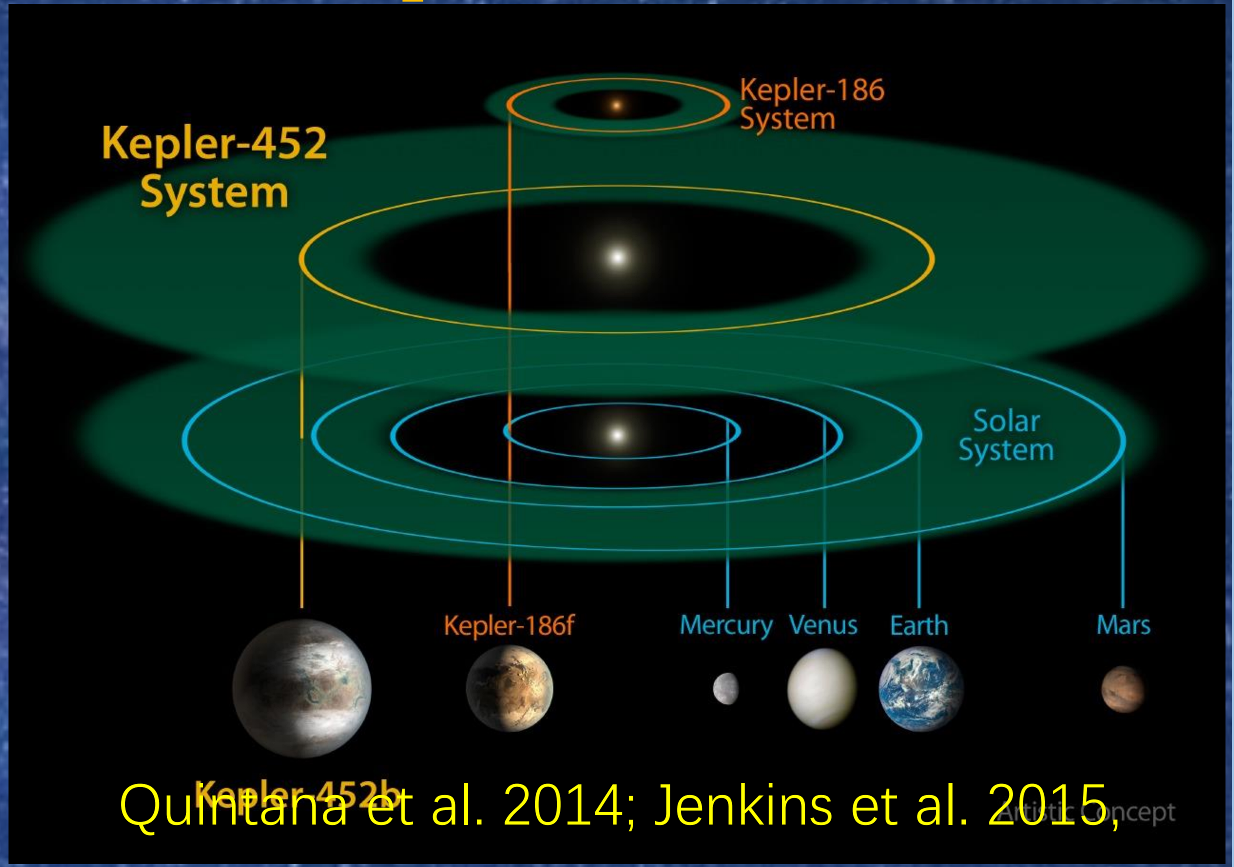
•R=1.5 $R_{\oplus}$

•M ~ 5 $M_{\oplus}$

Can super-Earths host life?

Super-Earths with more than 2 Earth masses

Kepler-452b



Quintana et al. 2014; Jenkins et al. 2015,

- Host star: 1.04 solar mass, ~1830 lys

Habitable planet:

- P=385 days
- $R=1.5\ R_{\oplus}$
- $M \sim 5\ M_{\oplus}$

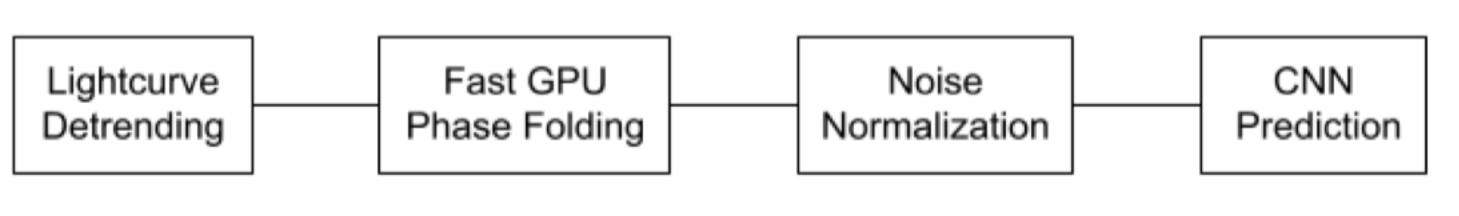
It is likely a false positive!!

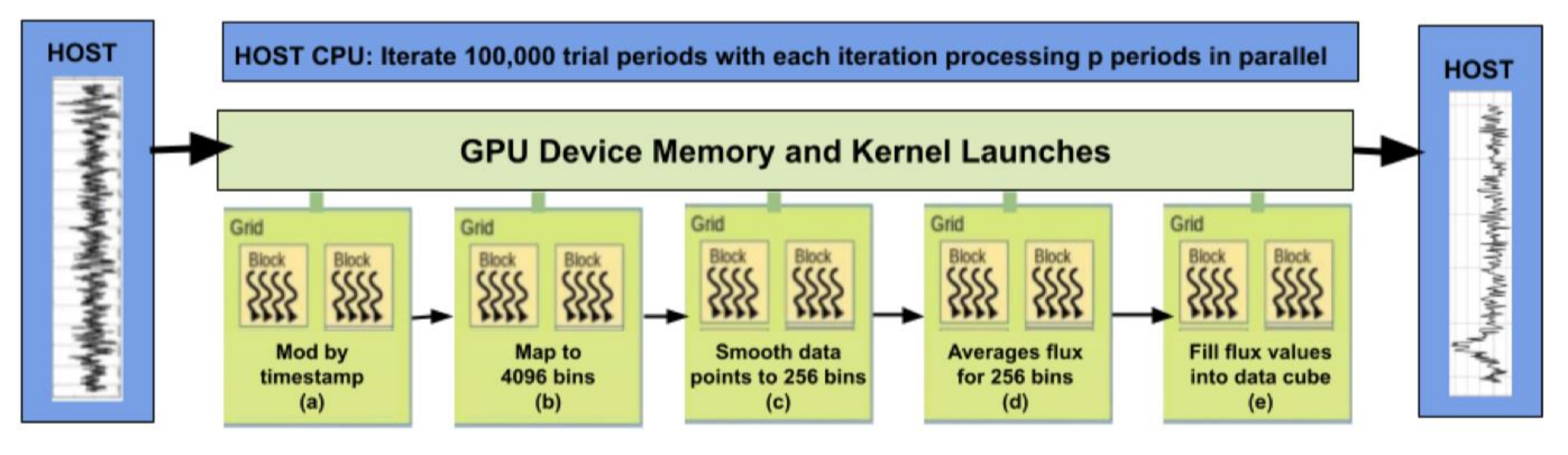
Kepler project scientist, Steve Howell, 2022

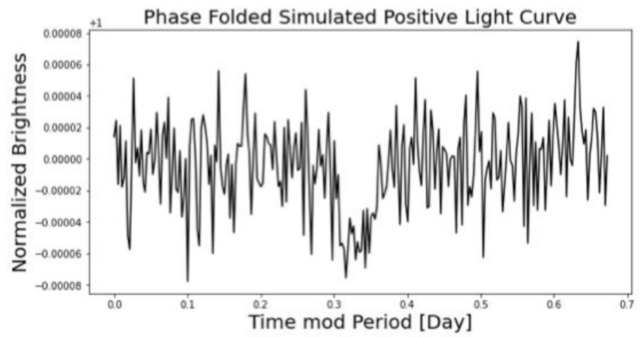
A super-Earth like Mustafar in Star War filled with lava flows

Searching for additional small planet signals in Kepler data with AI

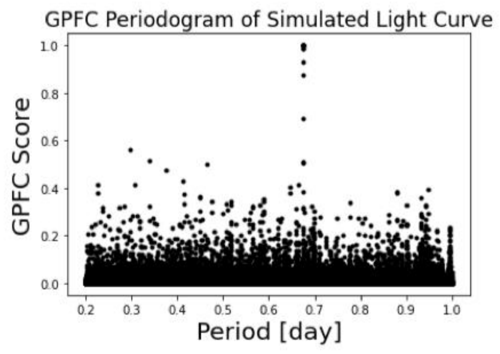
GPU Phase Folding and CNN (GPFC)



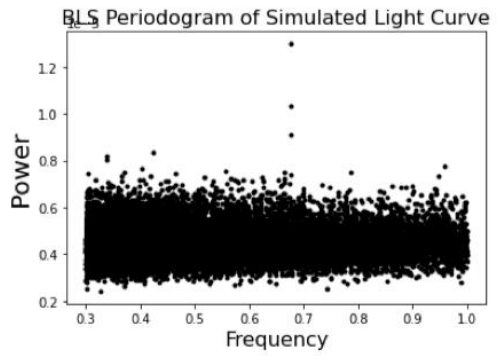




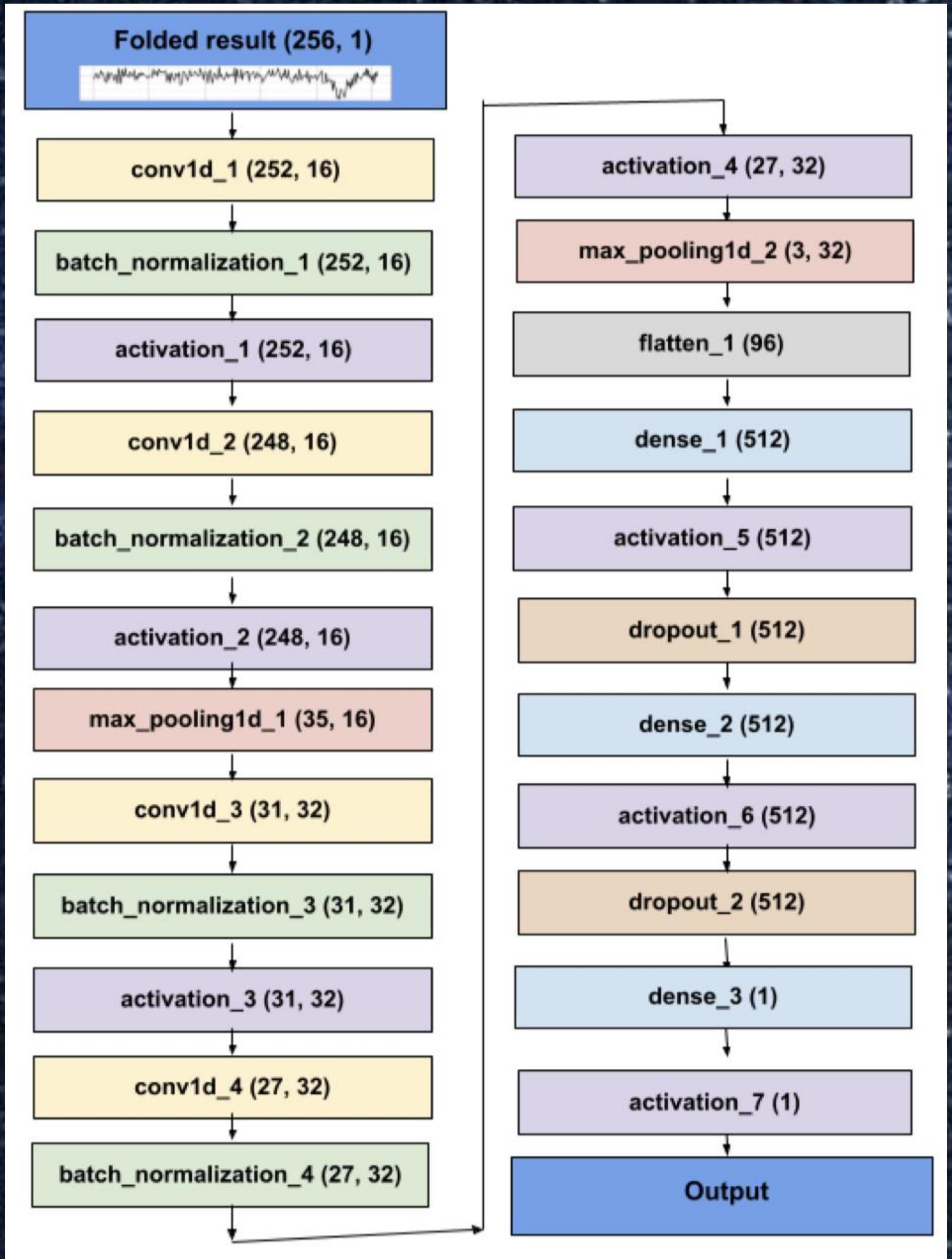
(a) Phase fold of a simulated light curve



(b) GPFC Periodogram



(c) BLS Periodogram

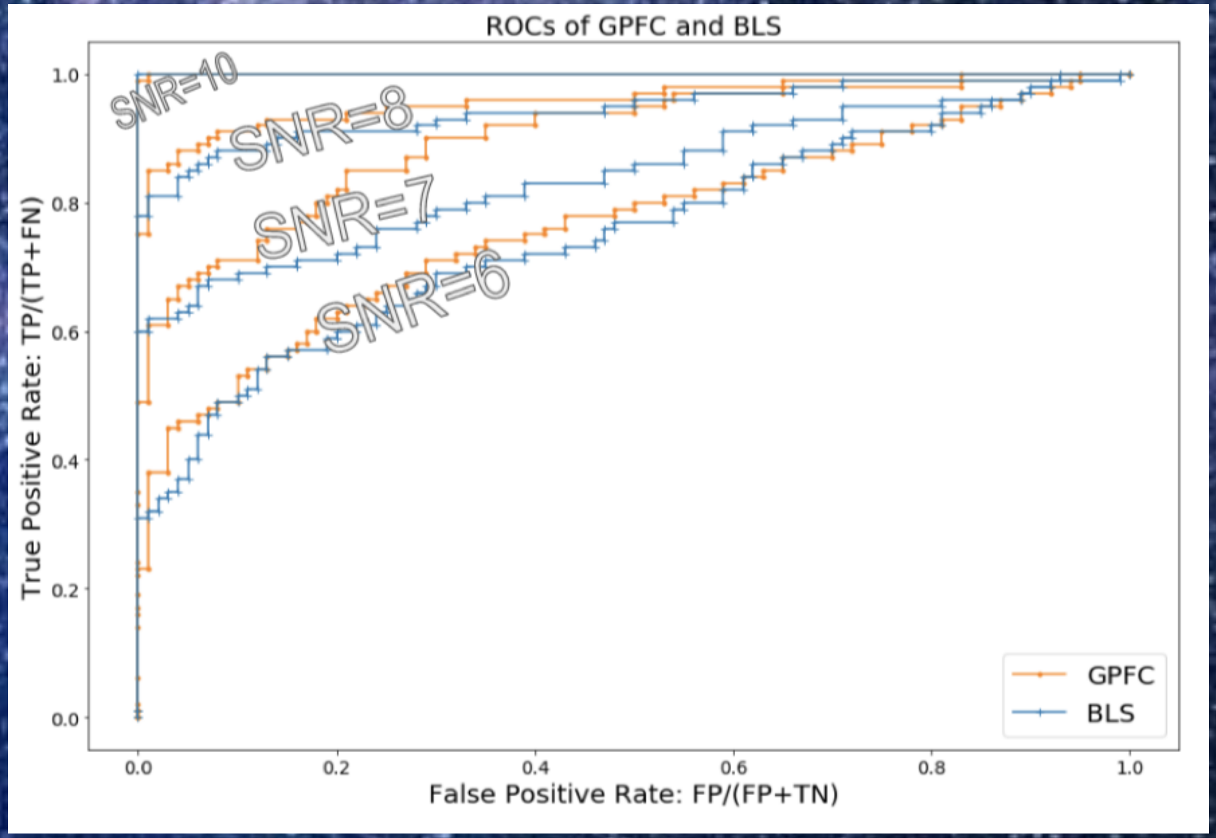


Wang , Ge + 2022, in prep

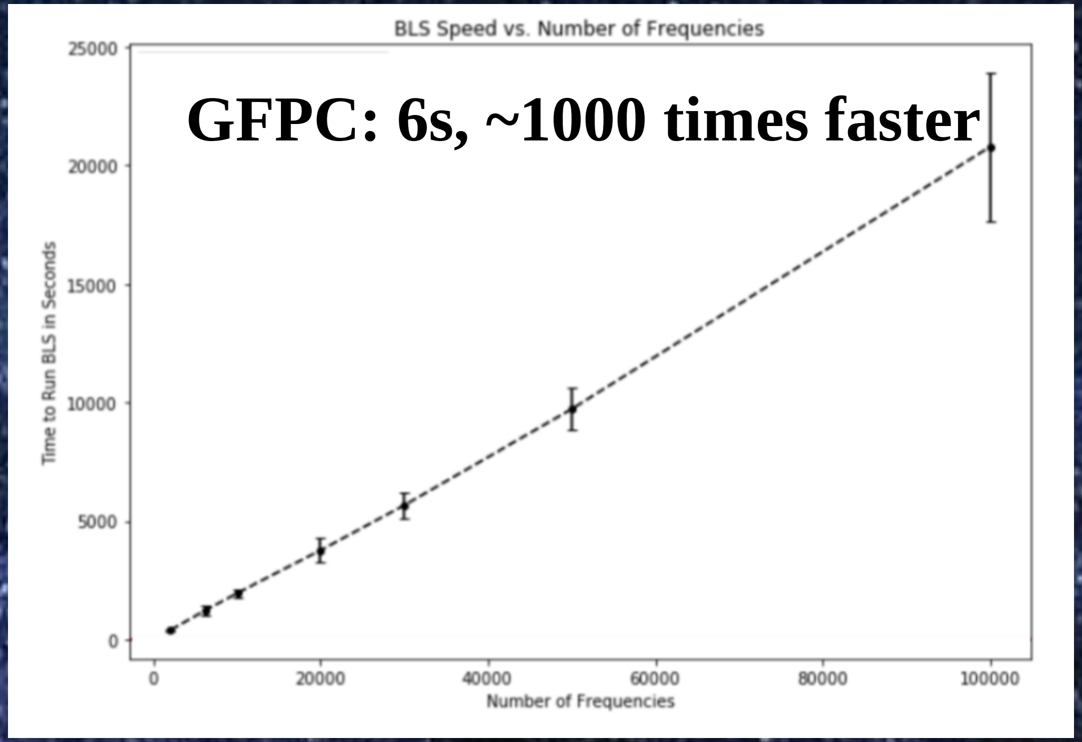
Searching for additional small planet signals in Kepler data with AI

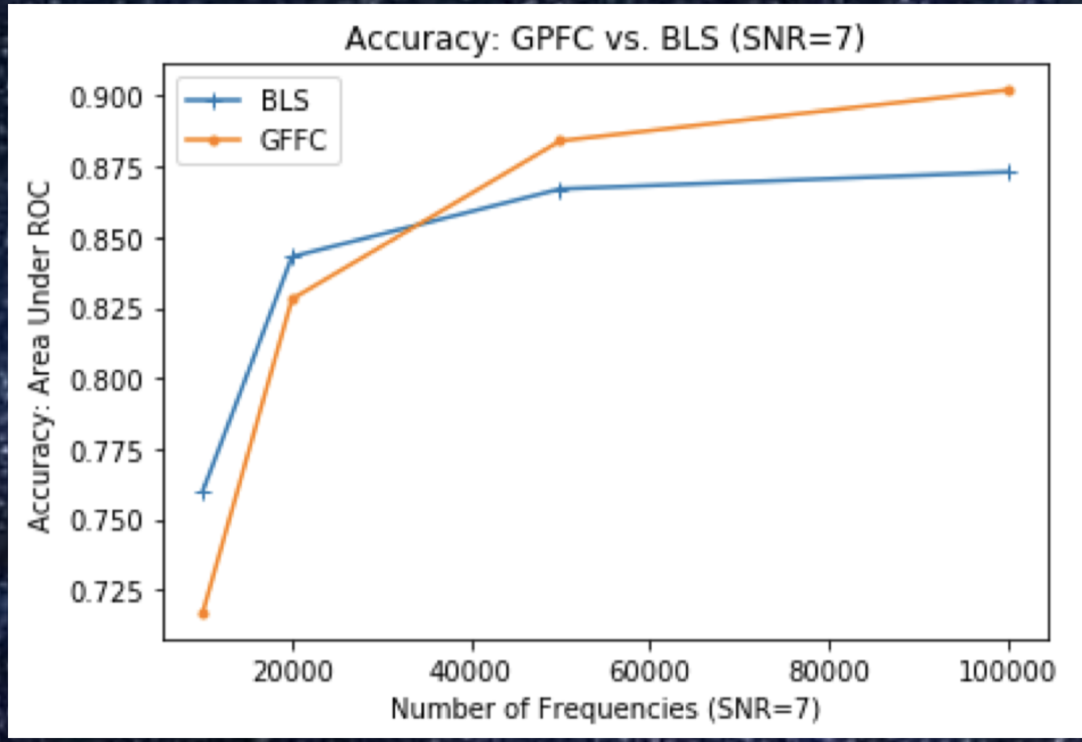
GPU Phase Folding and CNN (GPFC)

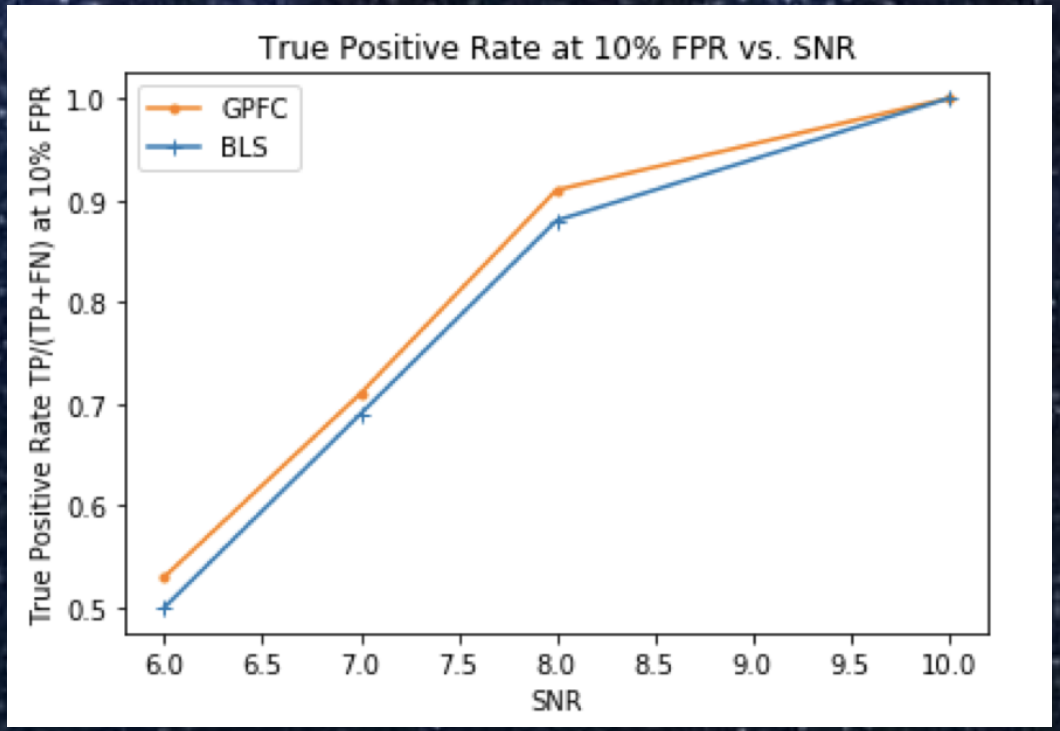
The Receiving Operating Characteristic curves for GPFC and BLS (with 20,000 frequencies)

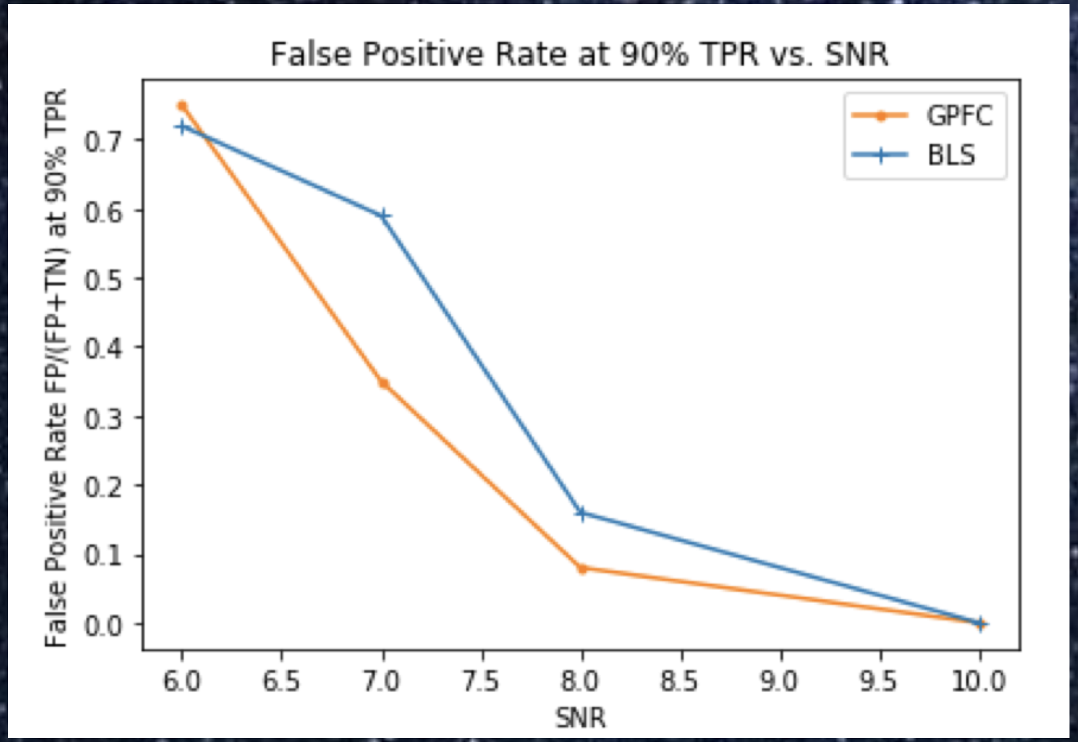


Speed of BLS vs. GPFC





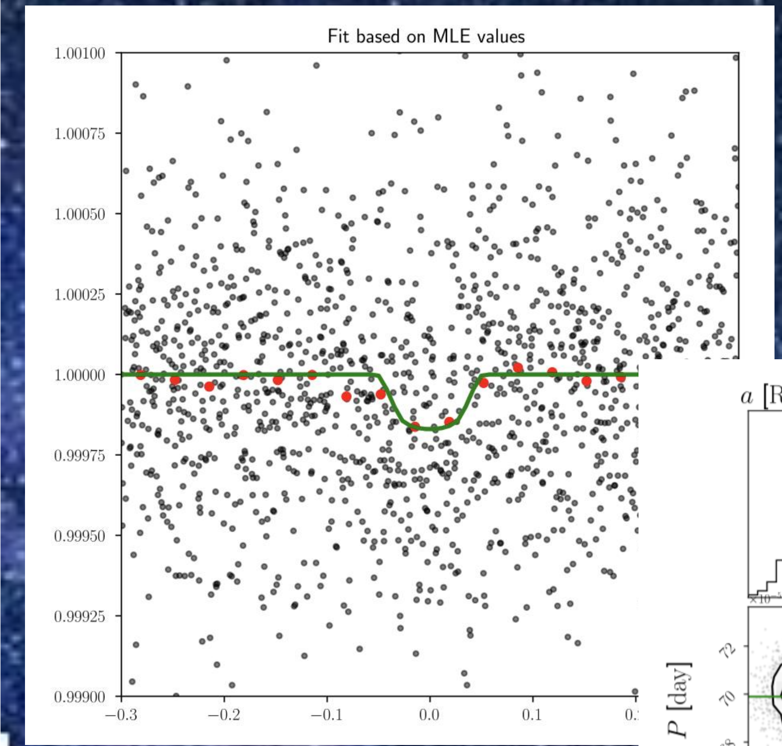


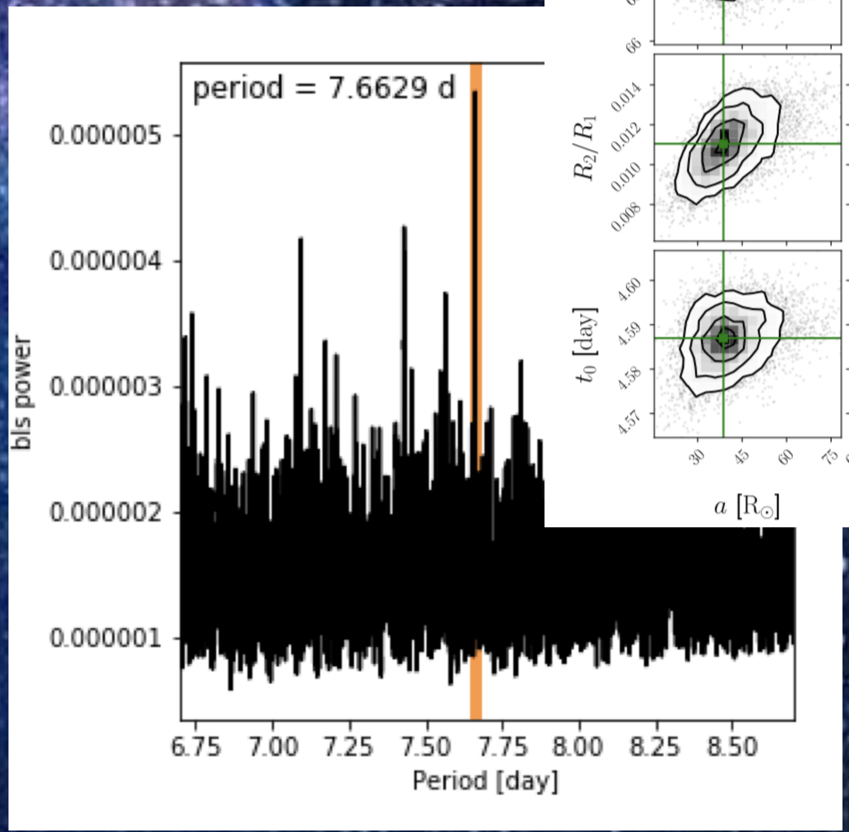


Wang , Ge+ 2022, in prep

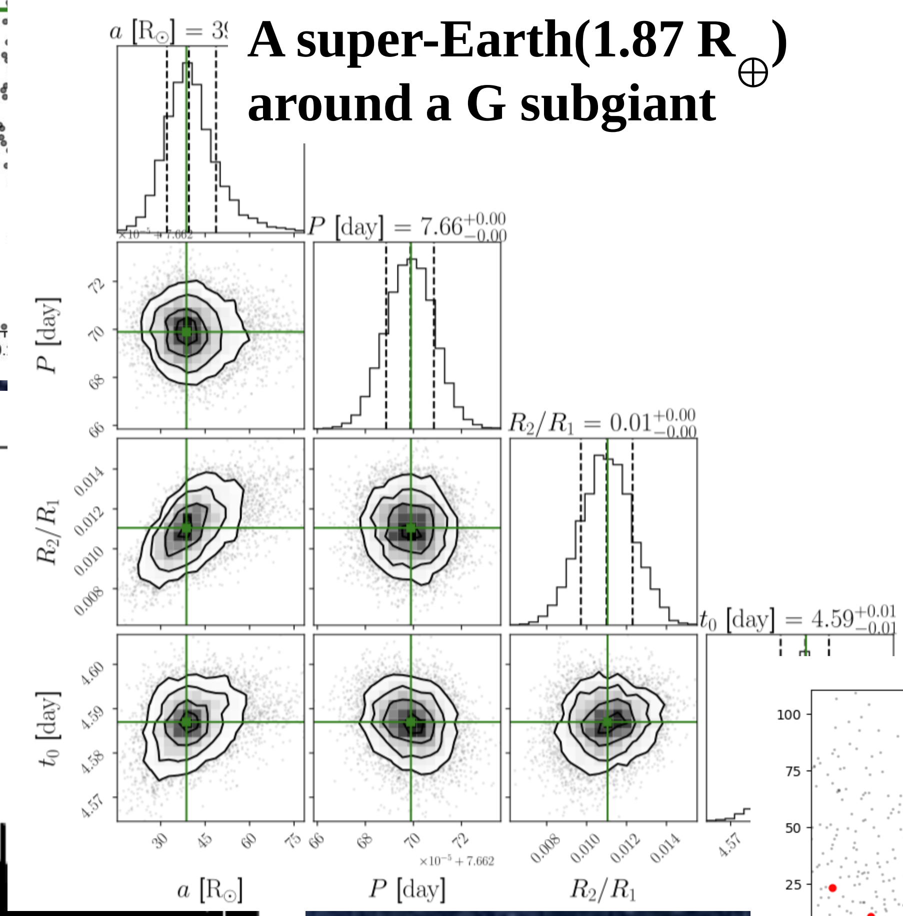
Searching for additional small planet signals in Kepler data with AI

GPU Phase Folding and CNN (GPFC)

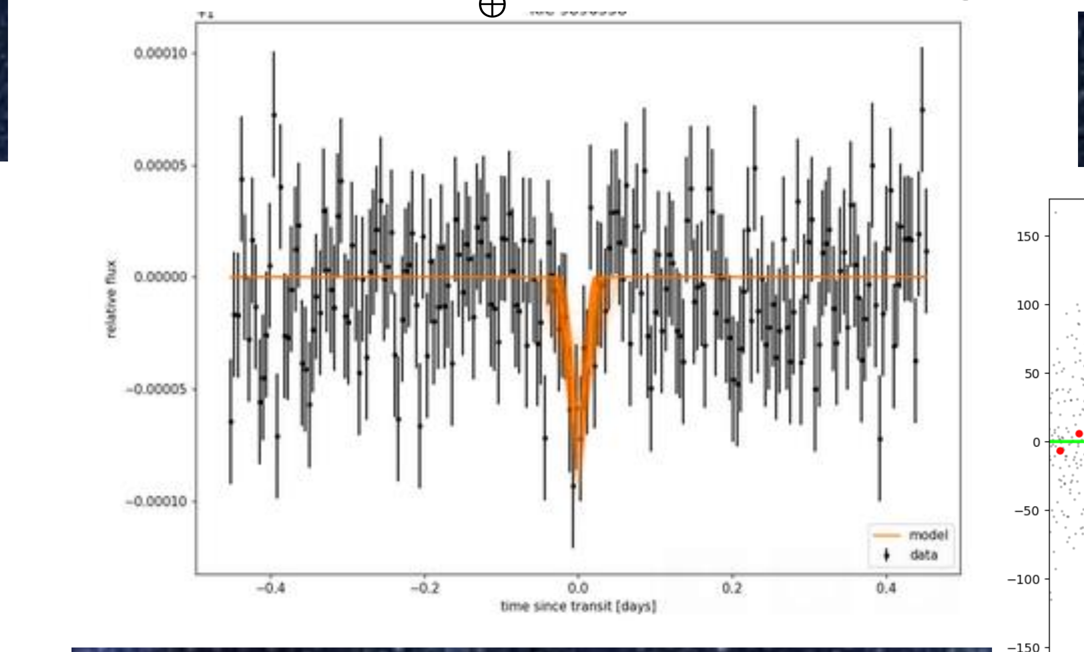




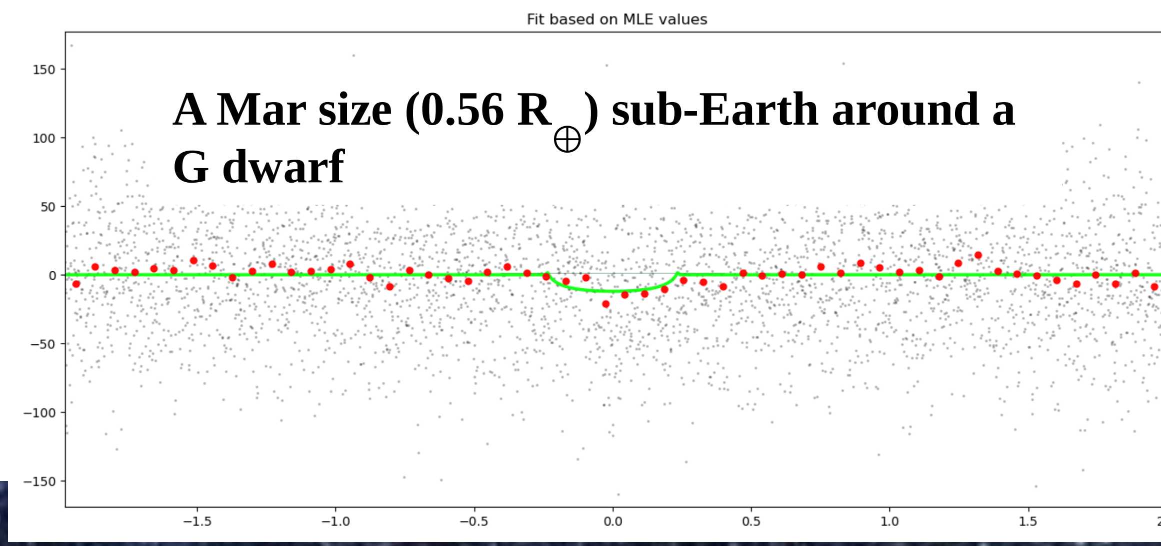
A super-Earth(1.87 R$_\oplus$) around a G subgiant



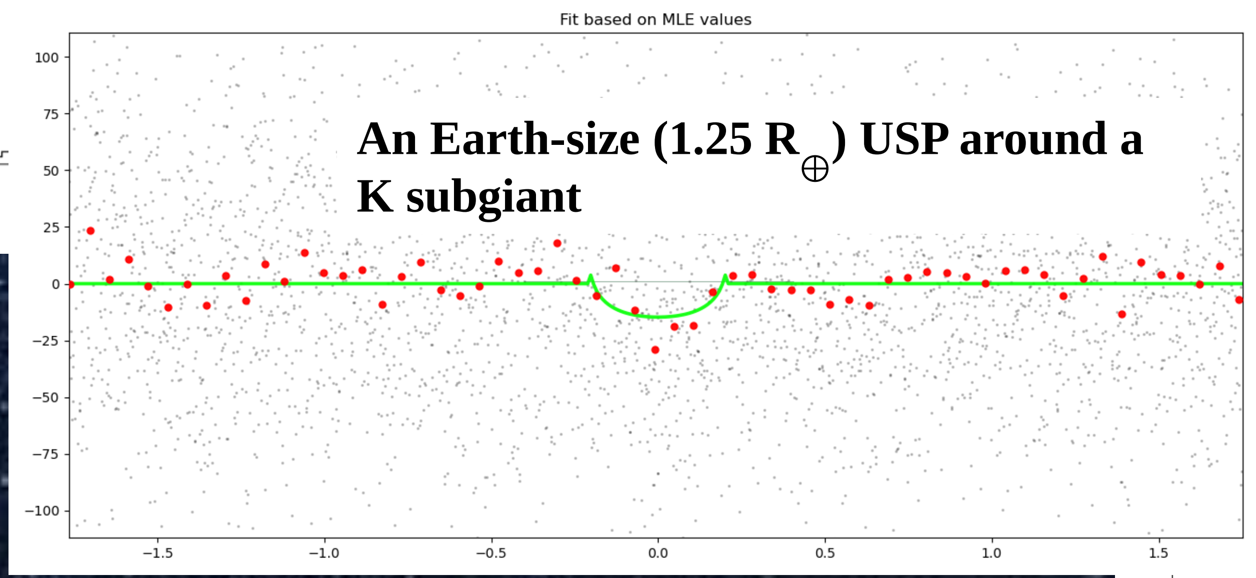
An Earth-size (0.98 R$_\oplus$) USP around a G subgiant



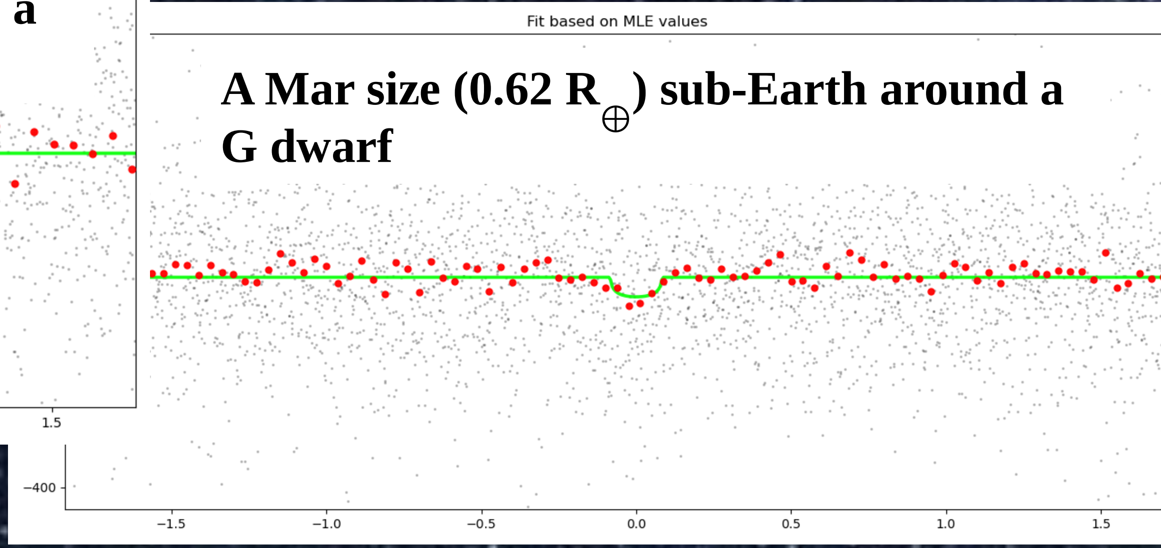
A Mar size (0.56 R$_\oplus$) sub-Earth around a G dwarf



An Earth-size (1.25 R$_\oplus$) USP around a K subgiant



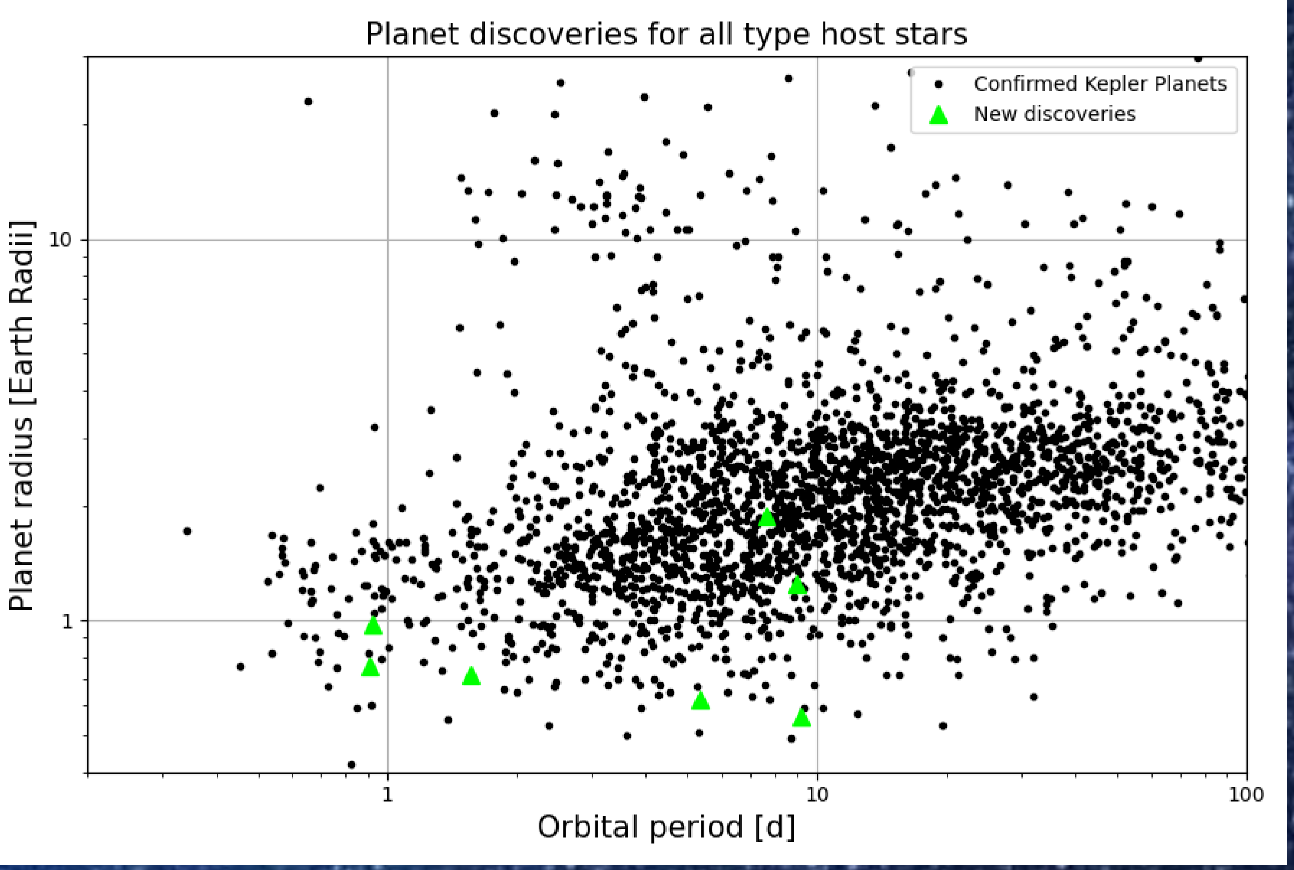
A Mar size (0.62 R$_\oplus$) sub-Earth around a G dwarf

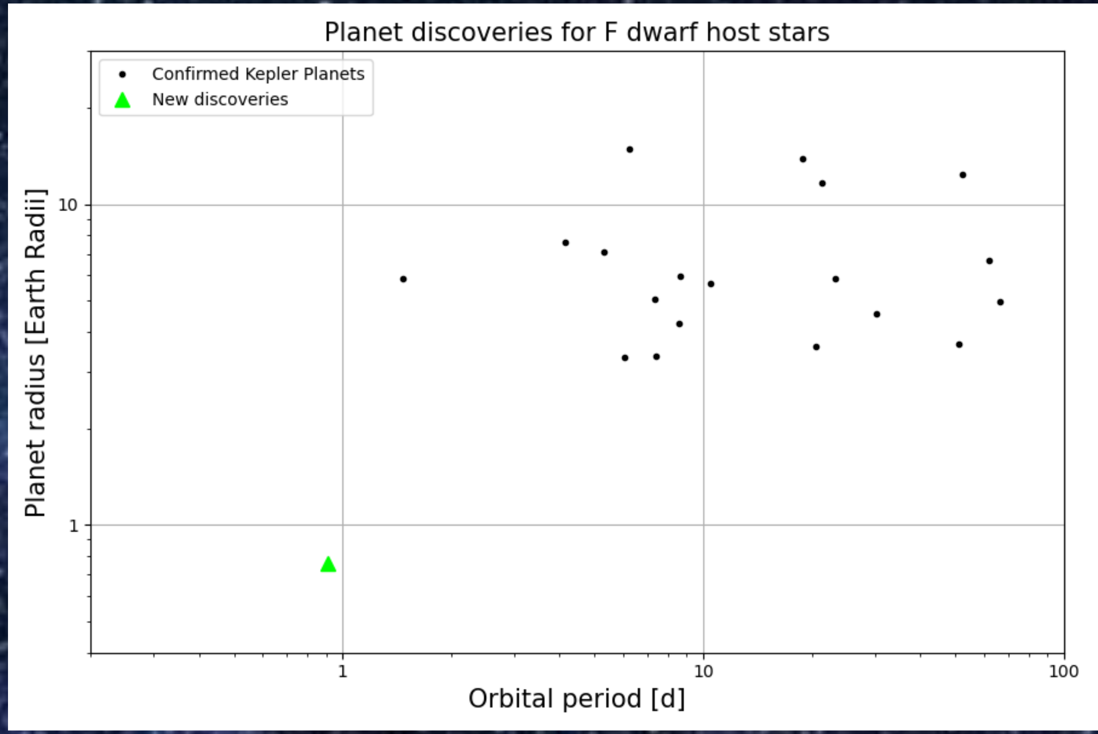


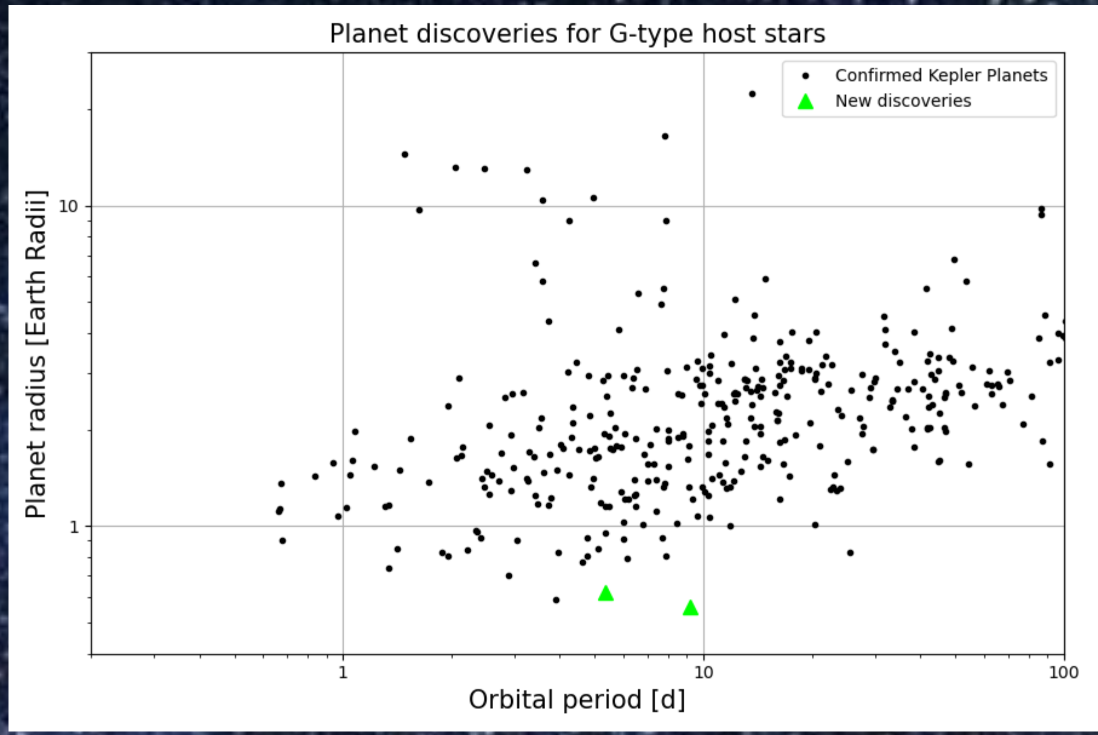
Wang, Ge + 2022, in prep; Chang, Ge + 2022, in prep; Fang, Ge + 2022, in prep

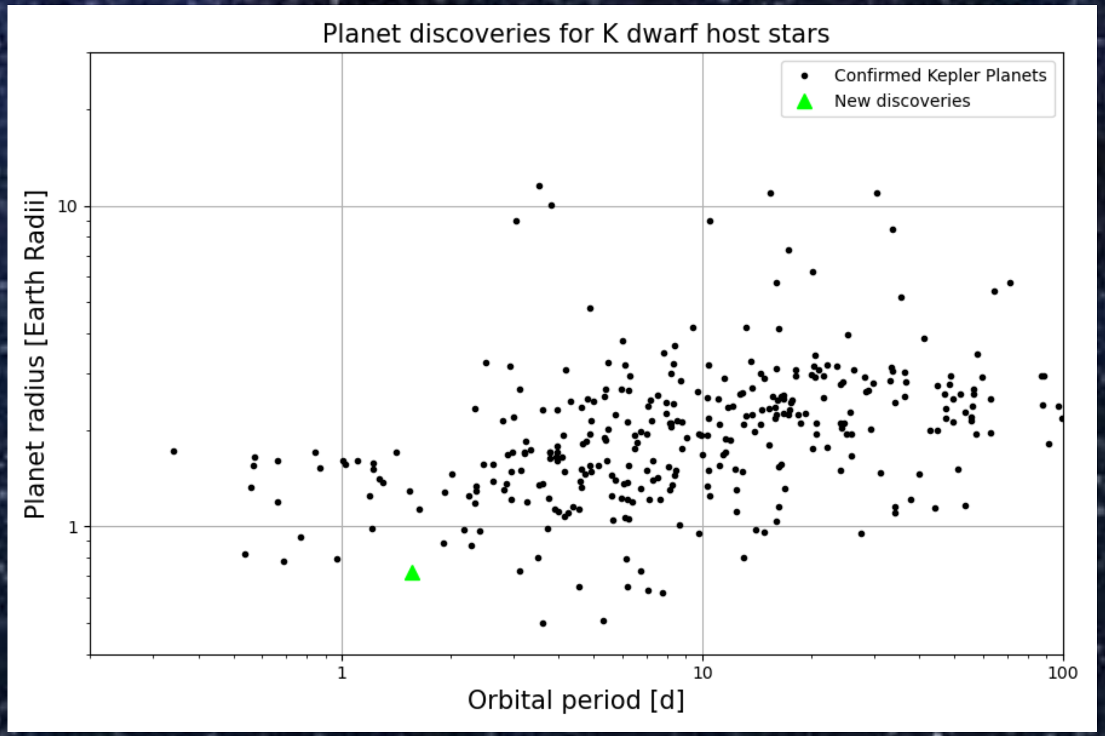
Searching for additional small planet signals in Kepler data with AI

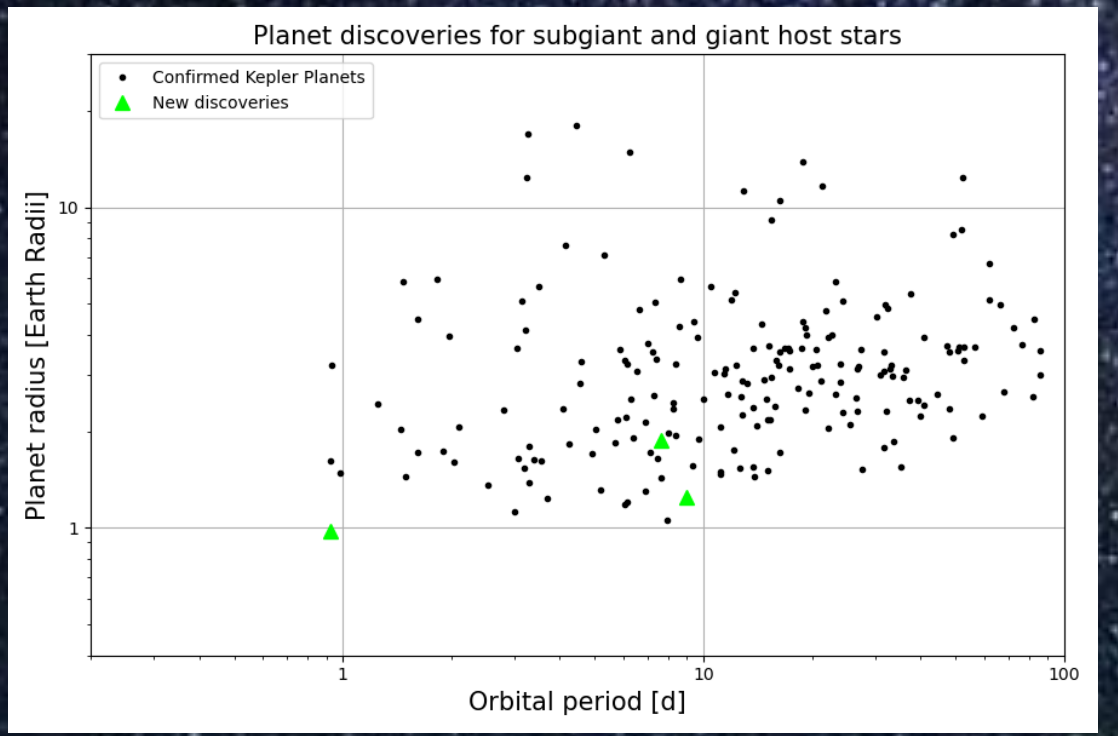
GPU Phase Folding and CNN (GPFC)









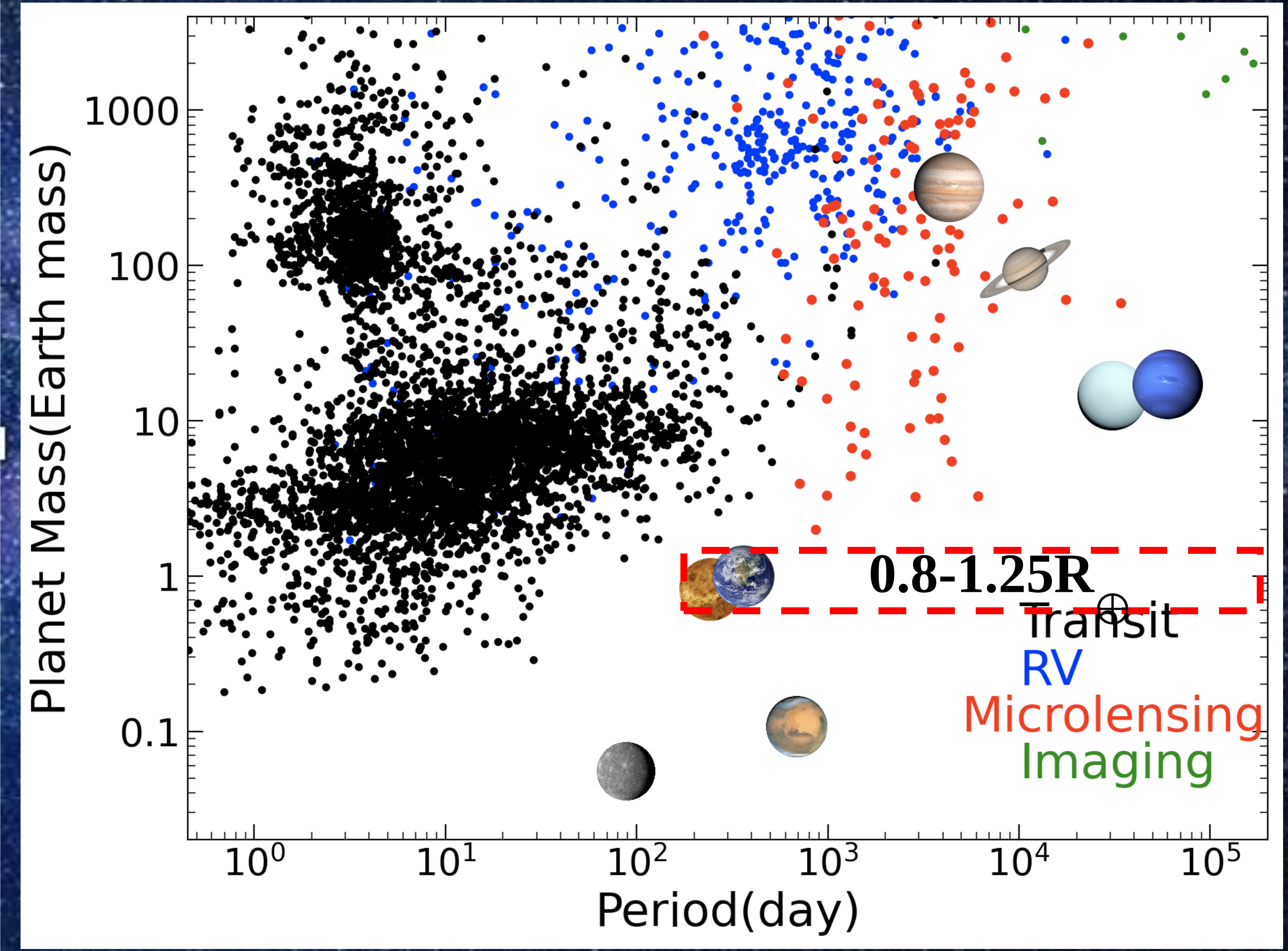


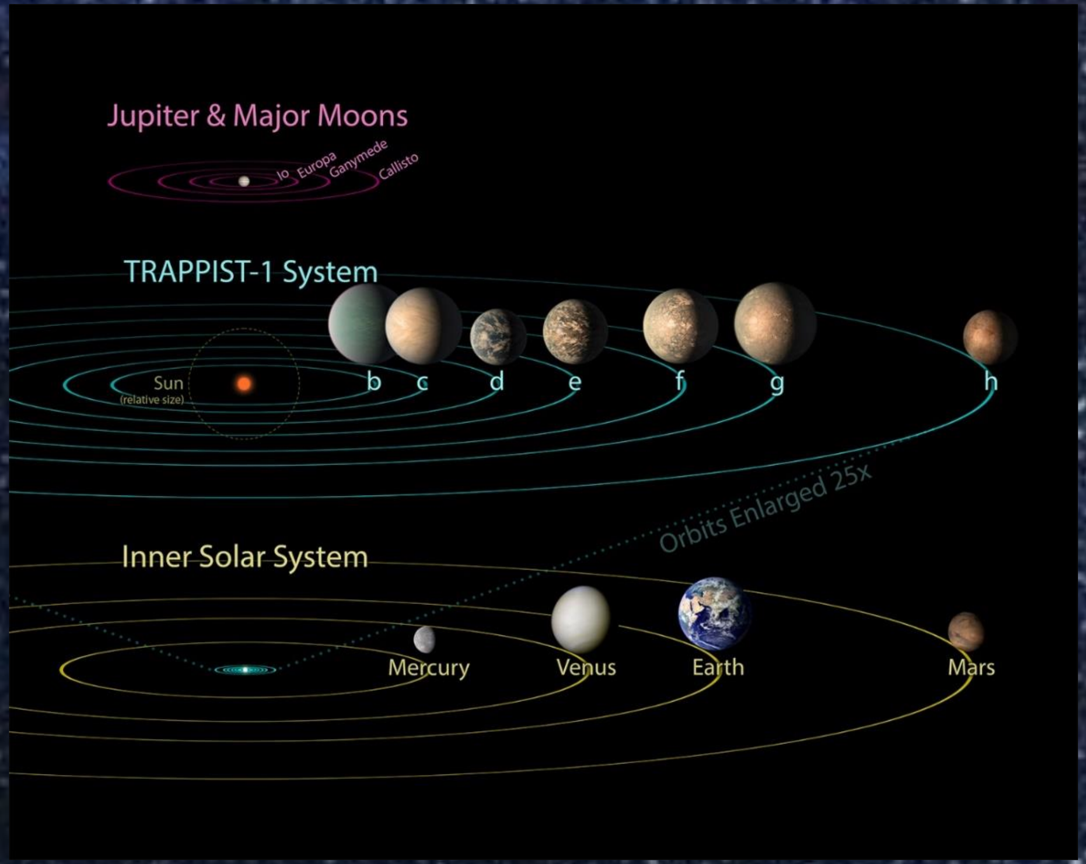
Wang, Ge + 2022, in prep; Chang, Ge + 2022, in prep; Fang, Ge + 2022, in prep

Current planet landscape

Surprising discoveries

- ~ 1/3 solar type stars host super-Earths and sub-Neptunes
- Only habitable Earth-size planets around M dwarfs

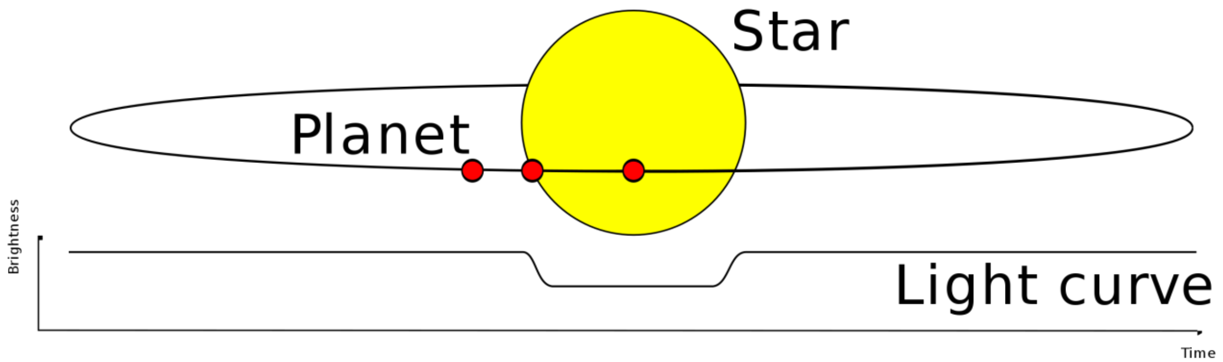


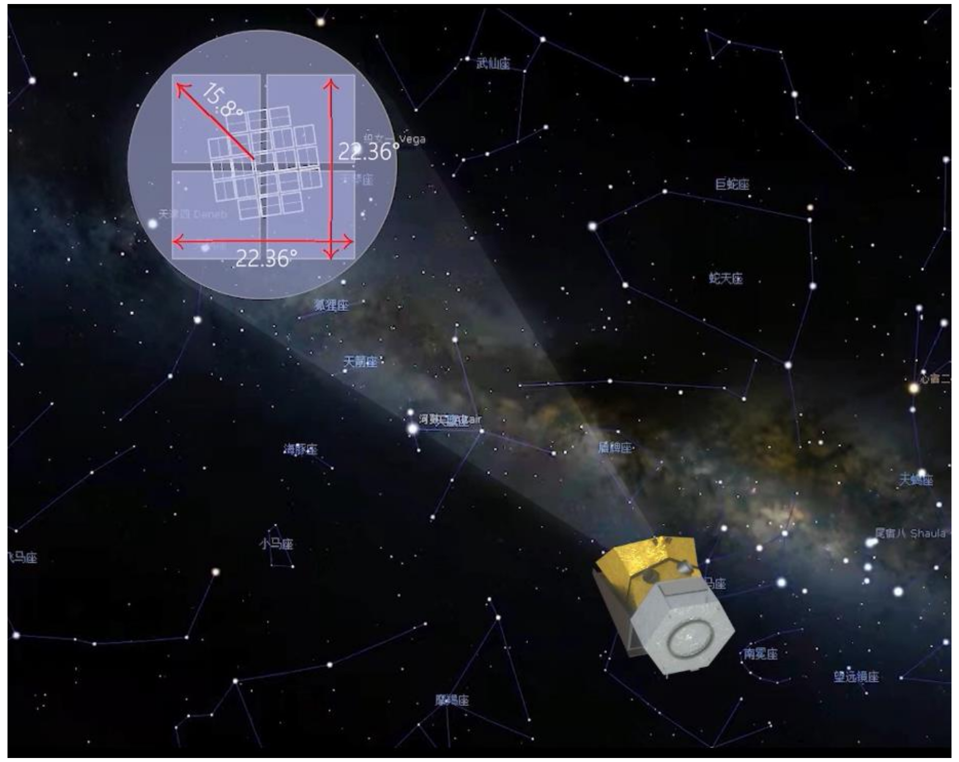


Is Earth alone?

ET Mission Overview

Transit





Six 30-cm wide field telescopes for transit survey

One 35-cm telescope for microlensing

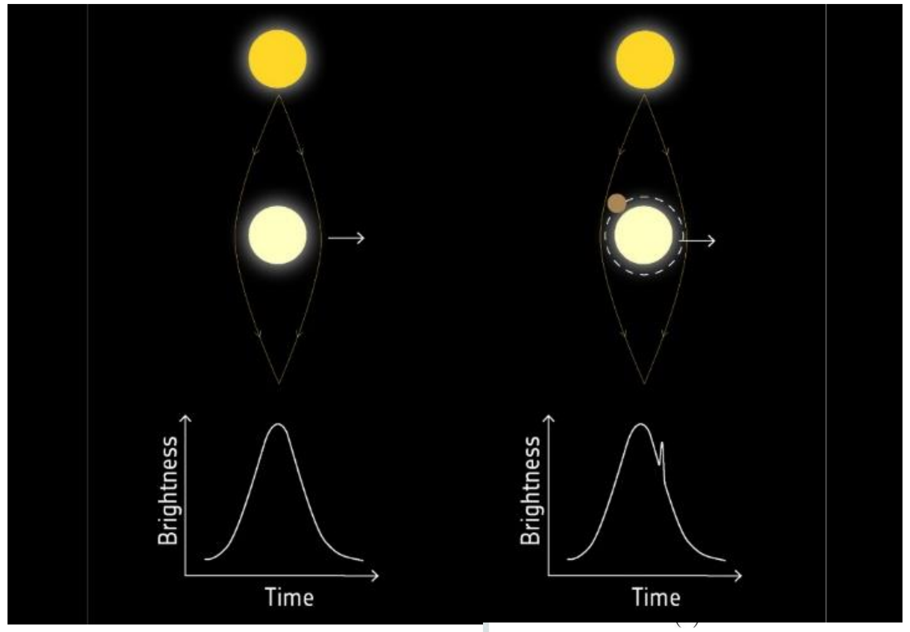
Monitoring 1.2 M FGKM dwarfs in the Kepler and its nearby field for 4 years

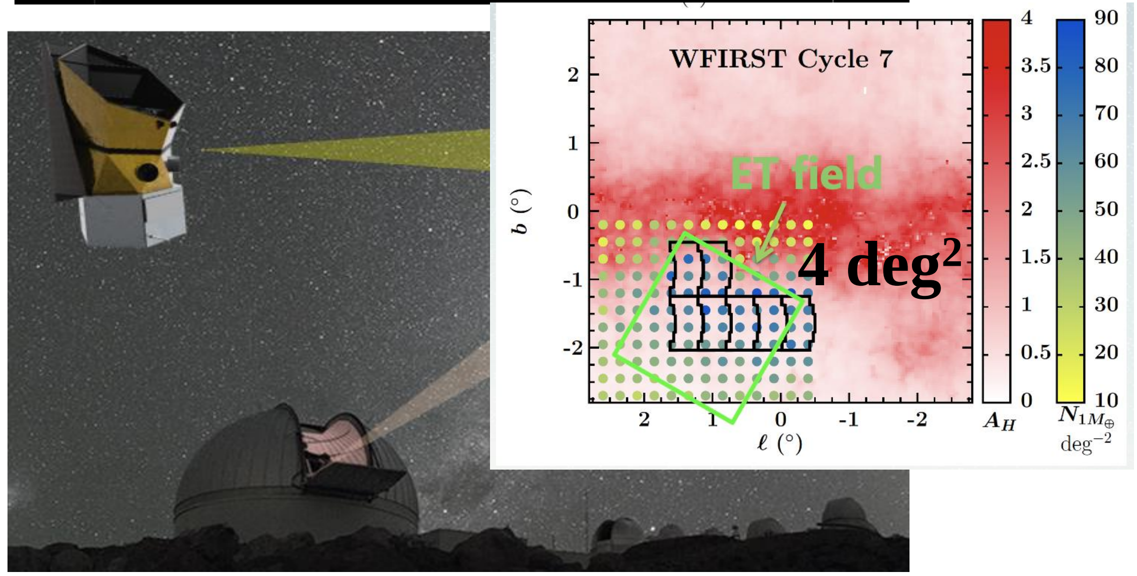
Scientific goals

- The first Earth 2.0
- Origin of Terrestrial planets

L2 halo orbit

Microlensing

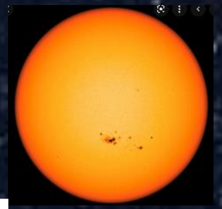




Monitoring 30M stars in the galaxy bulge simultaneously with the KMTNet

- Cold planets including free-floating planets & their origins

Photometry precision and target number determine the ET design



Golden targets： quiet sun-like stars

- Photometry precision determined by photon, instrument and stellar activity noises
  - ➢ Photon noise depends on aperture size
  - ➢ Instrument noise correlated with readout noise and thermal stability
  - ➢ Quiet stars have lower stellar noises

- Target number depends on magnitude limit and FOV
- Big FOV and deep depth
- Typical magnitude （~13 mag）

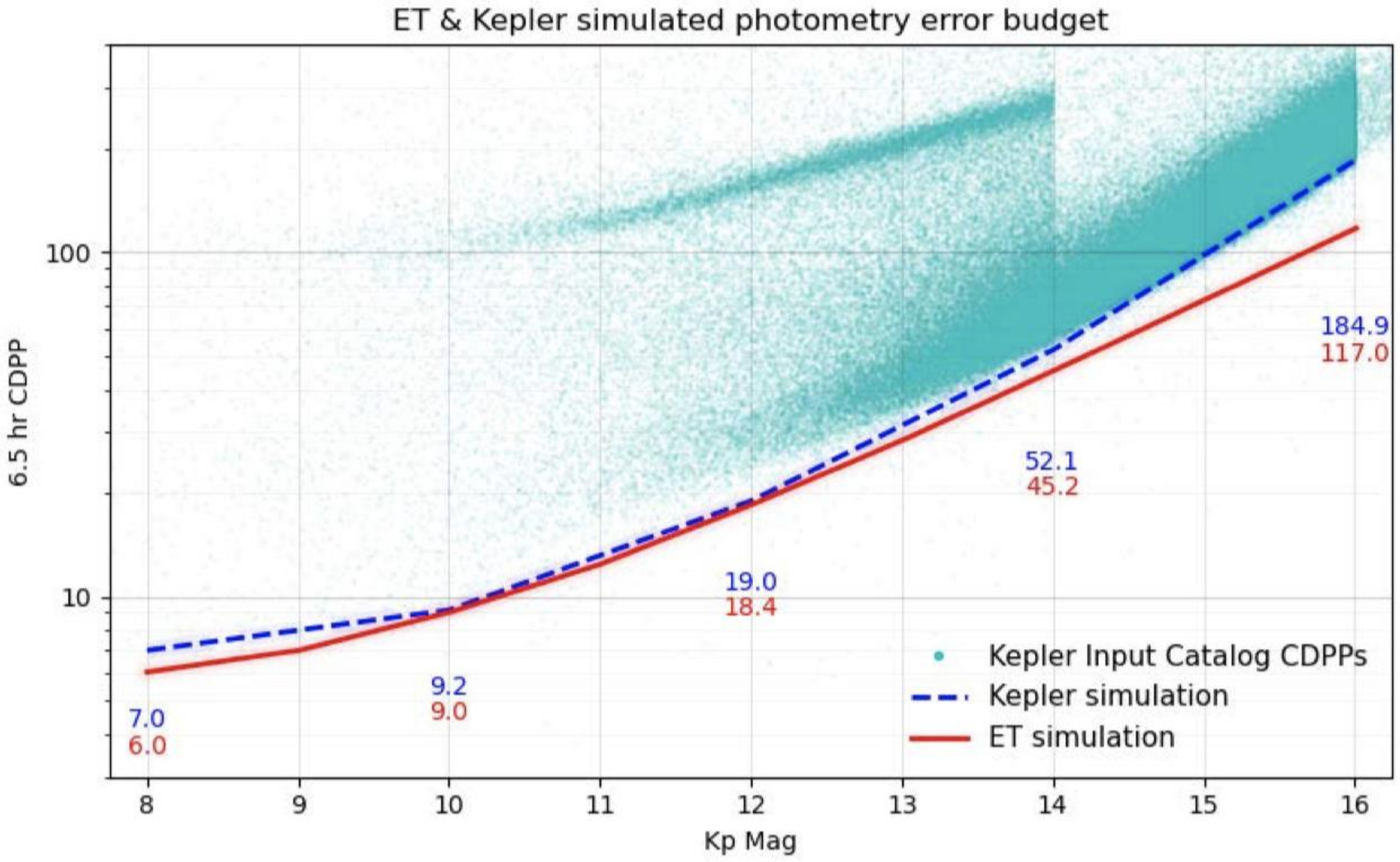
Kepler:
Aper.： 95cm
FOV:**105sqd**
Precision： 44 ppm
Golden targets： ~2500

ET:
Aper： 6x30cm, equiv. aper. 73cm
FOV： **500 sqd**
Precision ： 34 ppm
Golden targets： **~30000**

PLATO:
Aper.： 24x12cm
FOV： **2232 sqd**
Precision： 105 ppm
Golden targets： ~5000

Large aperture **Aperture size, FOV, precision and target num. optimized** **Big FOV**

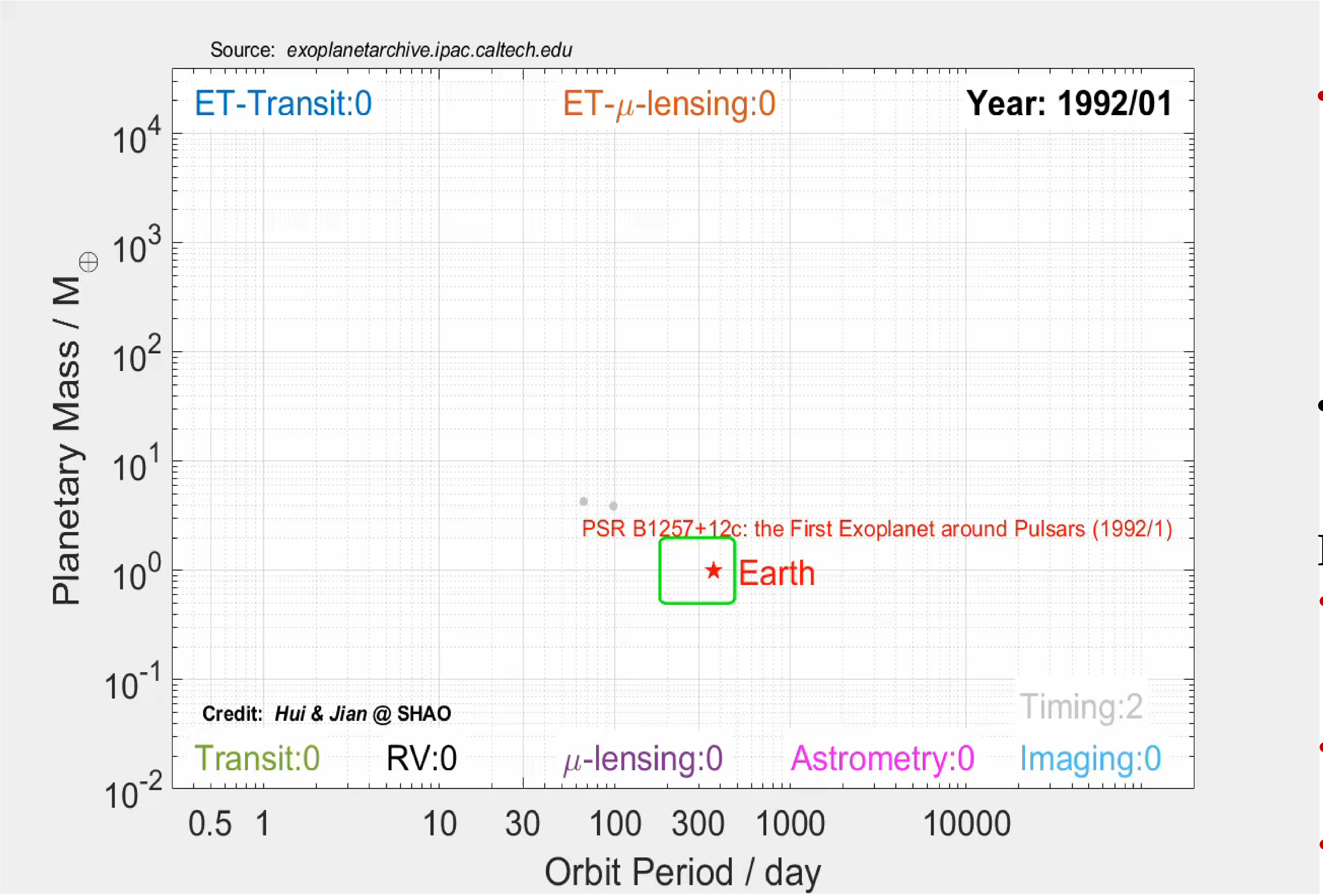
End-to-End Simulations of Kepler and ET Photometry Comparison



Key improvement over Kepler:

- Read noise ~4e$^-$ vs. 86 e$^-$
- Temperature control: ≤0.5℃ vs ~10 ℃

Planet discovery history and ET predictions



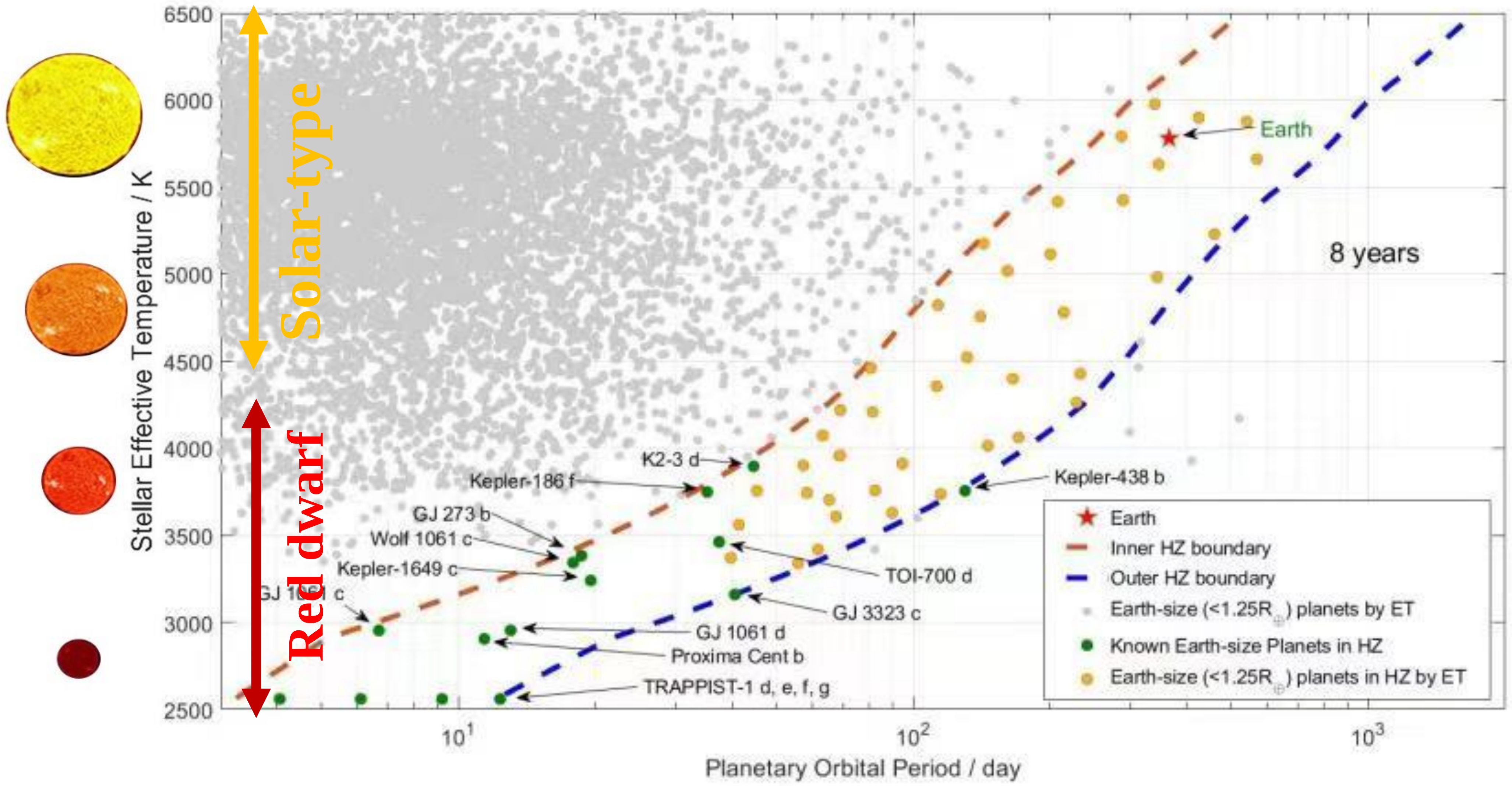
ET Key Science Goals

- **To discover ~5000 terrestrial like planets, increased by ~14 times of known ones， including ~17 Earth 2.0s, with orbital periods from ~ day to ~100 years, and interstellar space; to obtain masses for ~700 planets via TTVs**
- **~detect ~30K exoplanets, increased by ~6 times**

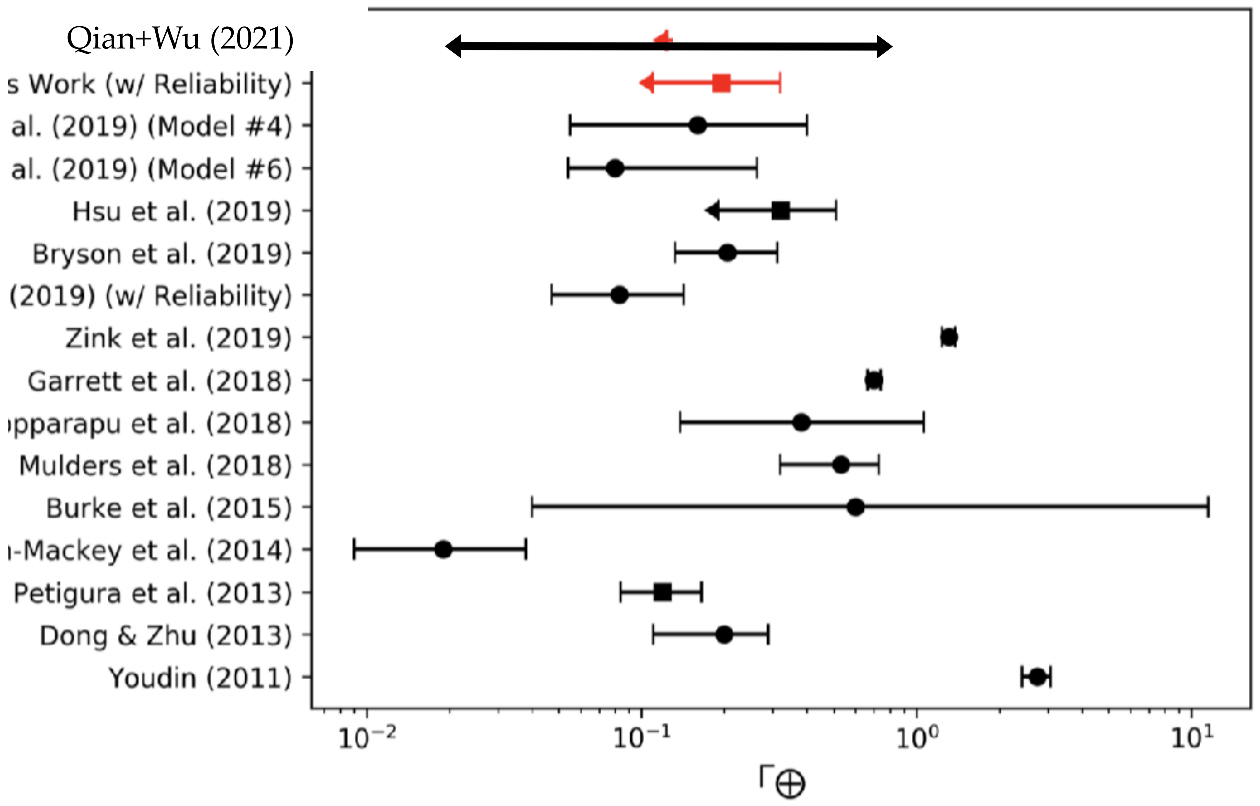
Key science questions：

- **How common are habitable Earth-like planets orbiting around solar-type stars?**
- **How do Earth-like planets form and evolve?**
- **What is the mass function and likely origin of free-floating low-mass planets?**

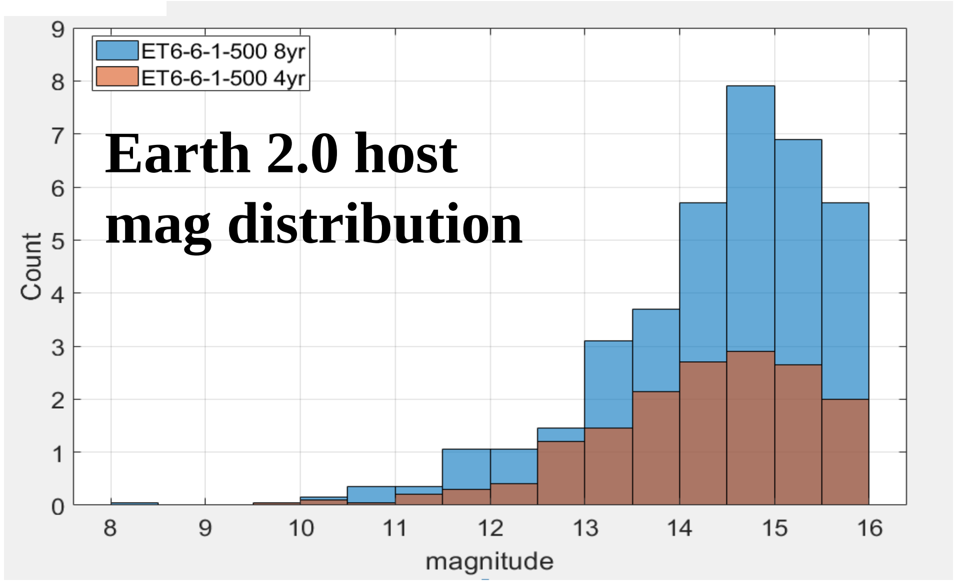
ET Key Sciences: the First Earth 2.0, Terrestrial Planet Formation, Cold Planets



Huge uncertainties in $\eta_{\oplus}$ measurements



Kunimoto+Matthews'20



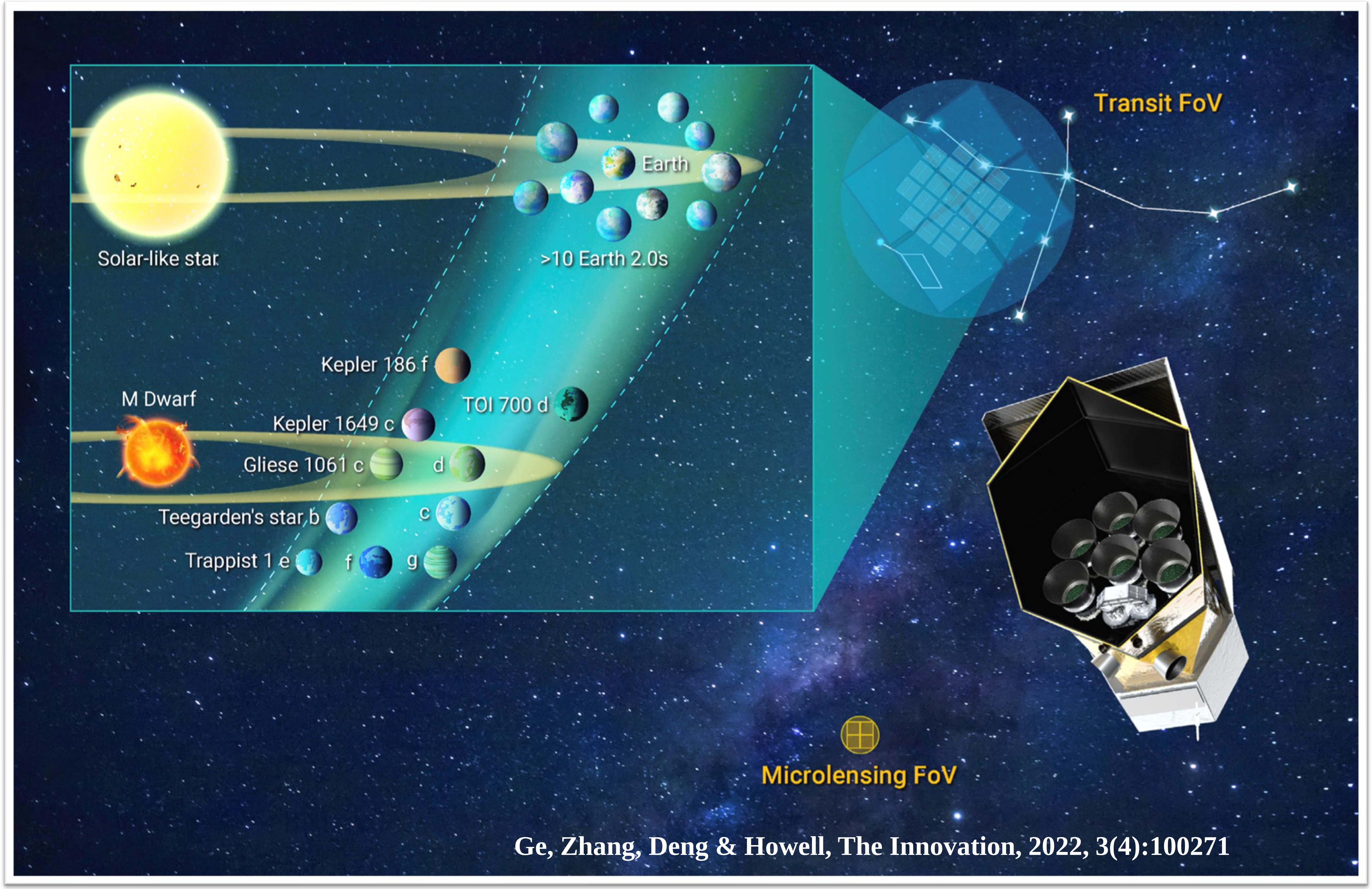
— **ET is expected to detect the first Earth 2.0!**

— **Assuming η_{Earth}=10%， we expect to detect 17-41 Earth 2.0s in 4-8yrs**

— **Accurately measure $\eta_{\oplus}$**

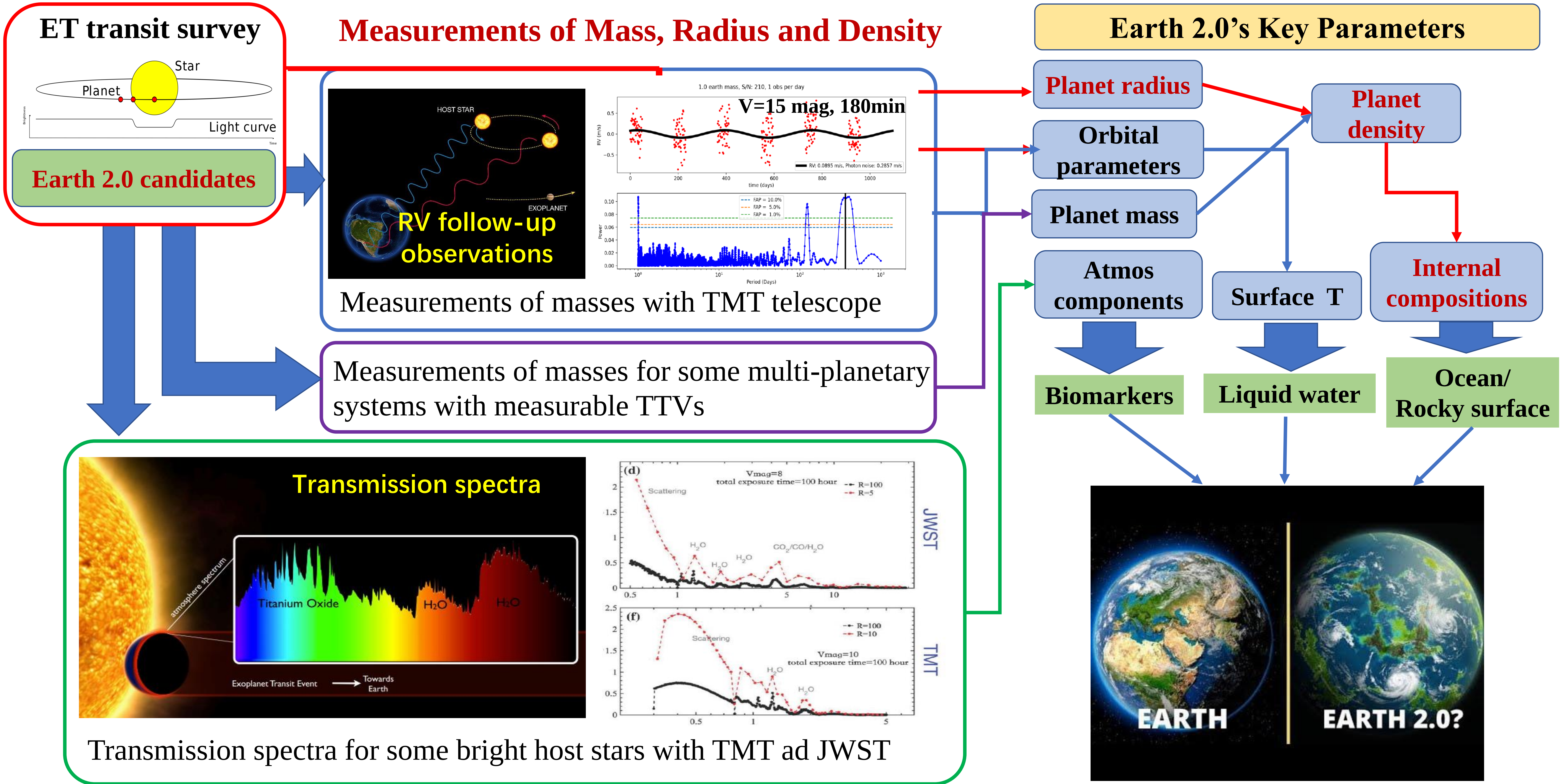
— **Host stars in the range of ~10-15mag can be followed up to characterize them**

ET卫星预计发现第一个地球2.0 （第二个地球）

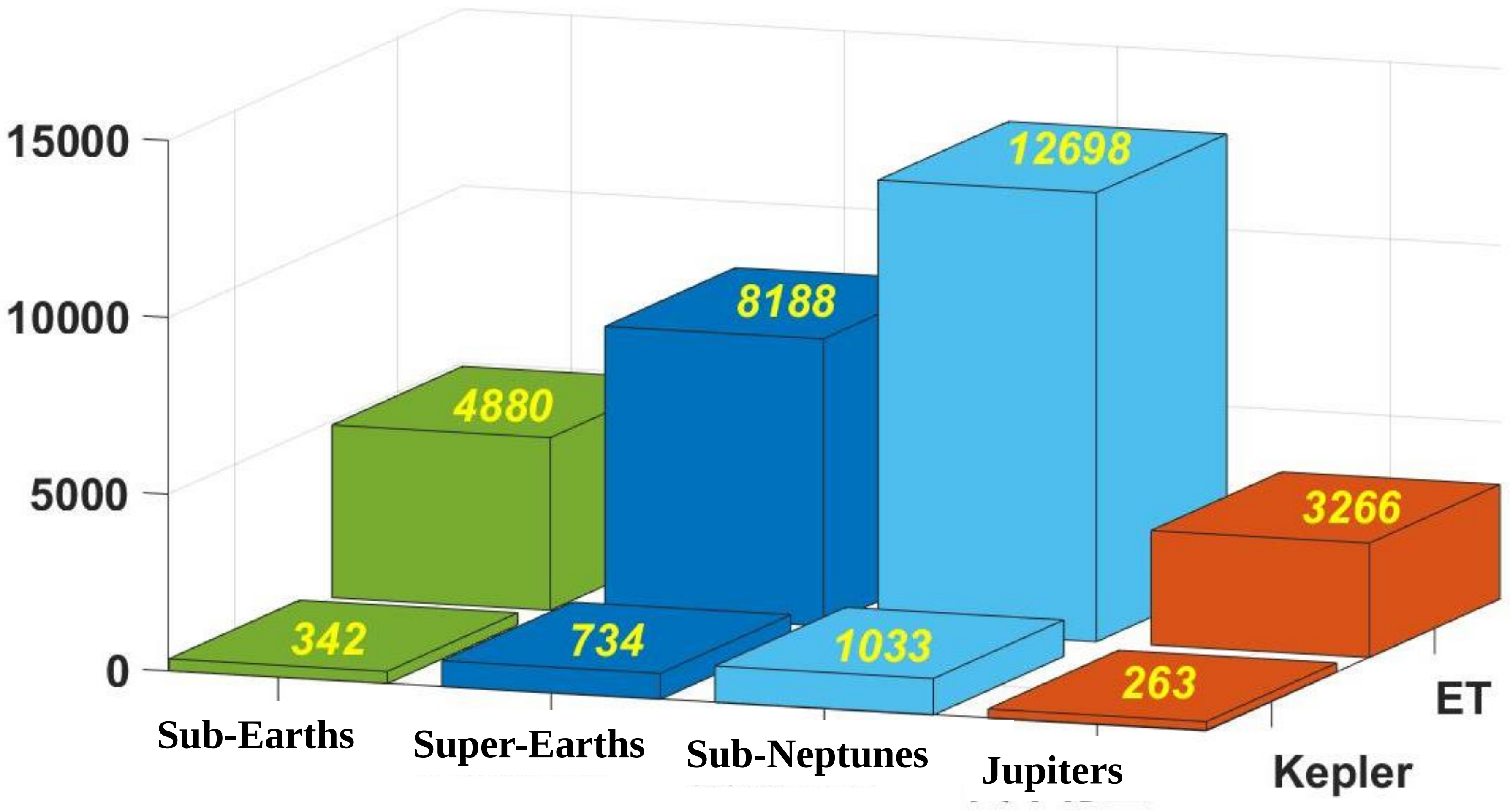


Ge, Zhang, Deng & Howell, The Innovation, 2022, 3(4):100271

ET Transit Survey + Follow-ups Optimal for Detecting Earth 2.0s



ET Key Sciences: the First Earth 2.0, Terrestrial Planet Formation, Cold Planets



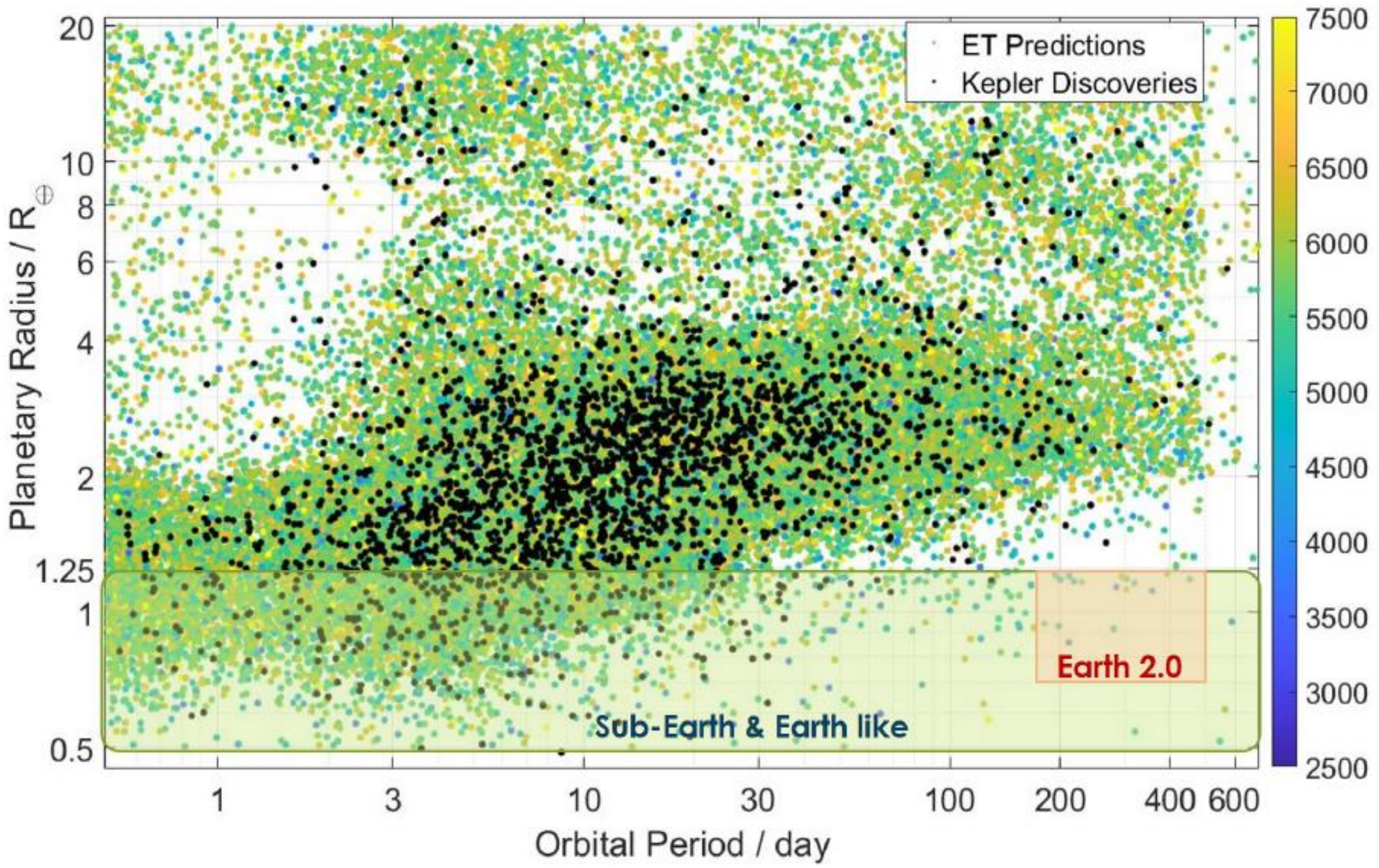
— Expect to detect ～5000 terrestrial like planets (~14xKepler)， help understand how terrestrial planets including Earth forms

- Measurements of occurrence rates, populations, orbit parameters, and environments
- Followup characterization: density, atmosphere compositions, habitability etc.

— ～30000 planets(~6x known), for testing planet formation and evolution models

- ~700 planet mass measurement via TTVs
- ~1000 solar like planet systems (~100x known systems)
- Tens of exomoons, exorings and exocomets
- Planets around stars with different mass, age (main sequence, giants, even WDs) , metallicity, environments (including binaries) and origins (such as halo, thin and thick disks, bulges etc).
- ~8000 asteroids

ET Key Sciences: the First Earth 2.0, Terrestrial Planet Formation, Cold Planets



— Expect to detect ~5000 terrestrial like planets (~14xKepler), help understand how terrestrial planets including Earth forms

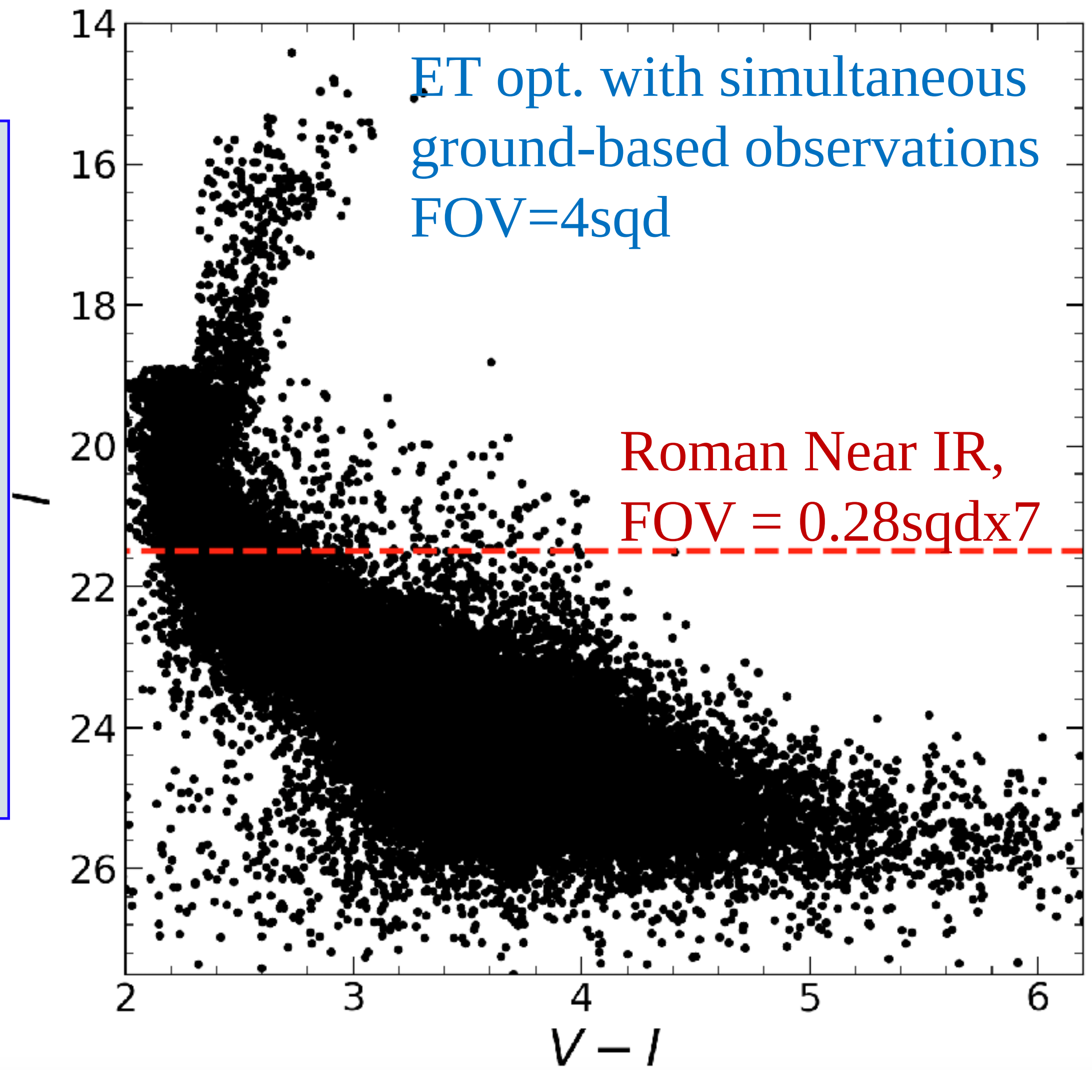
- Measurements of occurrence rates, populations, orbit parameters, and environments
- Followup characterization: density, atmosphere compositions, habitability etc.

— ~30000 planets(~6x known), for testing planet formation and evolution models

- ~700 planet mass measurement via TTVs
- ~1000 solar like planet systems (~100x known systems)
- Tens of exomoons, exorings and exocomets
- Planets around stars with different mass, age (main sequence, giants, even WDs) , metallicity, environments (including binaries) and origins (such as halo, thin and thick disks, bulges etc).
- ~8000 asteroids

ET Key Sciences: the First Earth 2.0, Terrestrial Planet Formation, Cold Planets

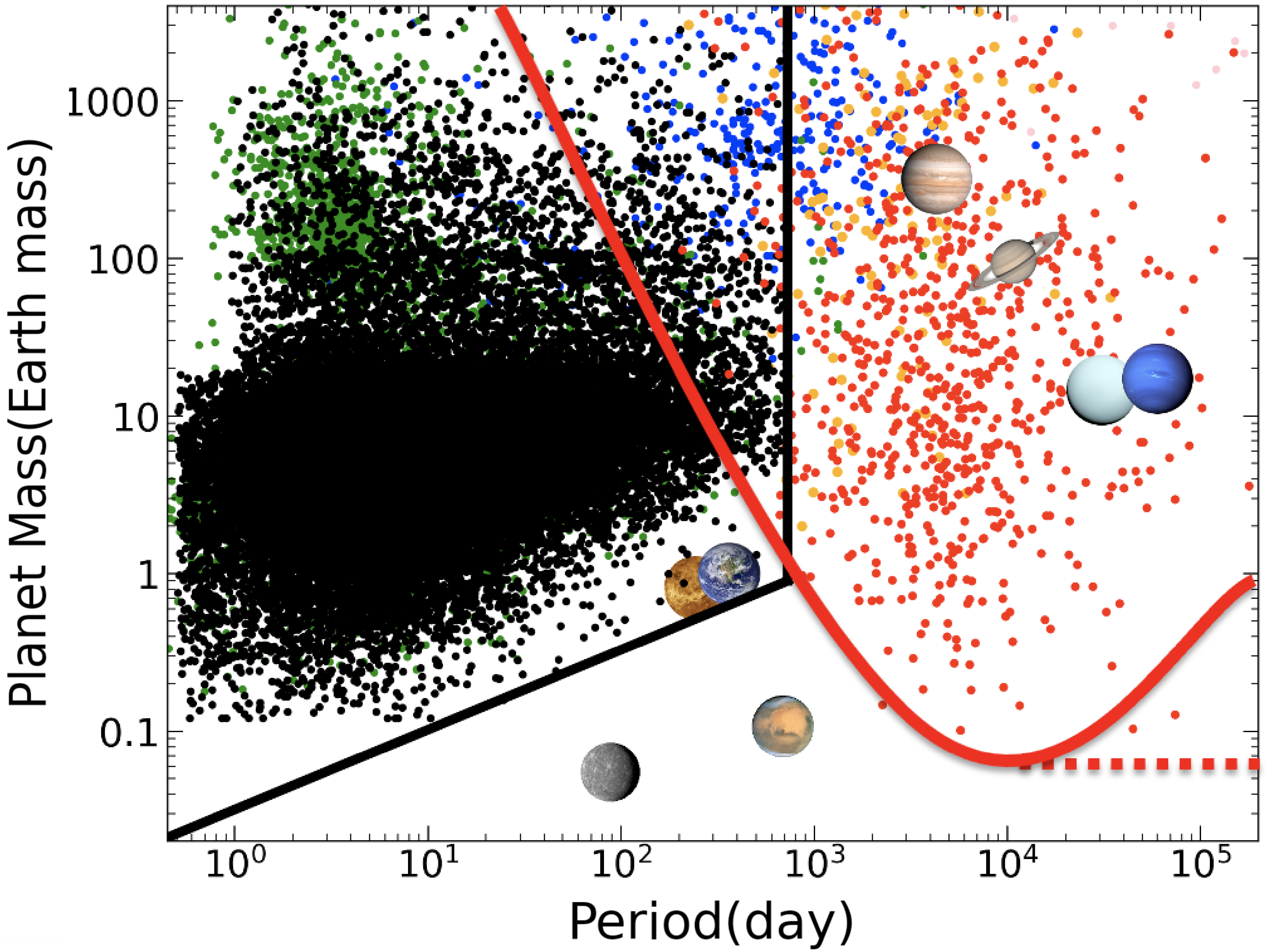
— To date only ~ 12 free-floating planet candidates， ~ 150 cold planets, only ~ 25 with mass measurements
— ET will have comparable yields to Roman, over **10x known cold and free-floating planets**
— ET will observe with the ground-based KMTnet to measure masses for ~1/4 number of planets using parallaxes
— Expect to have breakthroughs in studying cold/free floating planets.



ET microlensing vs. Roman microlensing

	Time	Orbit	Diameter	Observing time (days)	Cadence	Mag Limit (σ=0.2mag)	Target number	Cold planets (with masses)	Cold Earths (with masses)	Free-floating planets (with masses)
ROMAN	2027-	L2	2.4m	360	15min	H < 24.0	1.7×10^8	~650(~160)	~60(~15)	~900(~20)
ET (4yrs)	2027-	L2	35cm	730	10min	I<20.9	3.5×10^7	~430(~130)	~40(~12)	~600(~150)
ET (8yrs)								~860(~260)	~80(~24)	~1200(~300)

ET: the First Space Mission to Cover the Entire Planet Survey Space



- ET transit survey
- ET microlensing survey

Free-floating planets

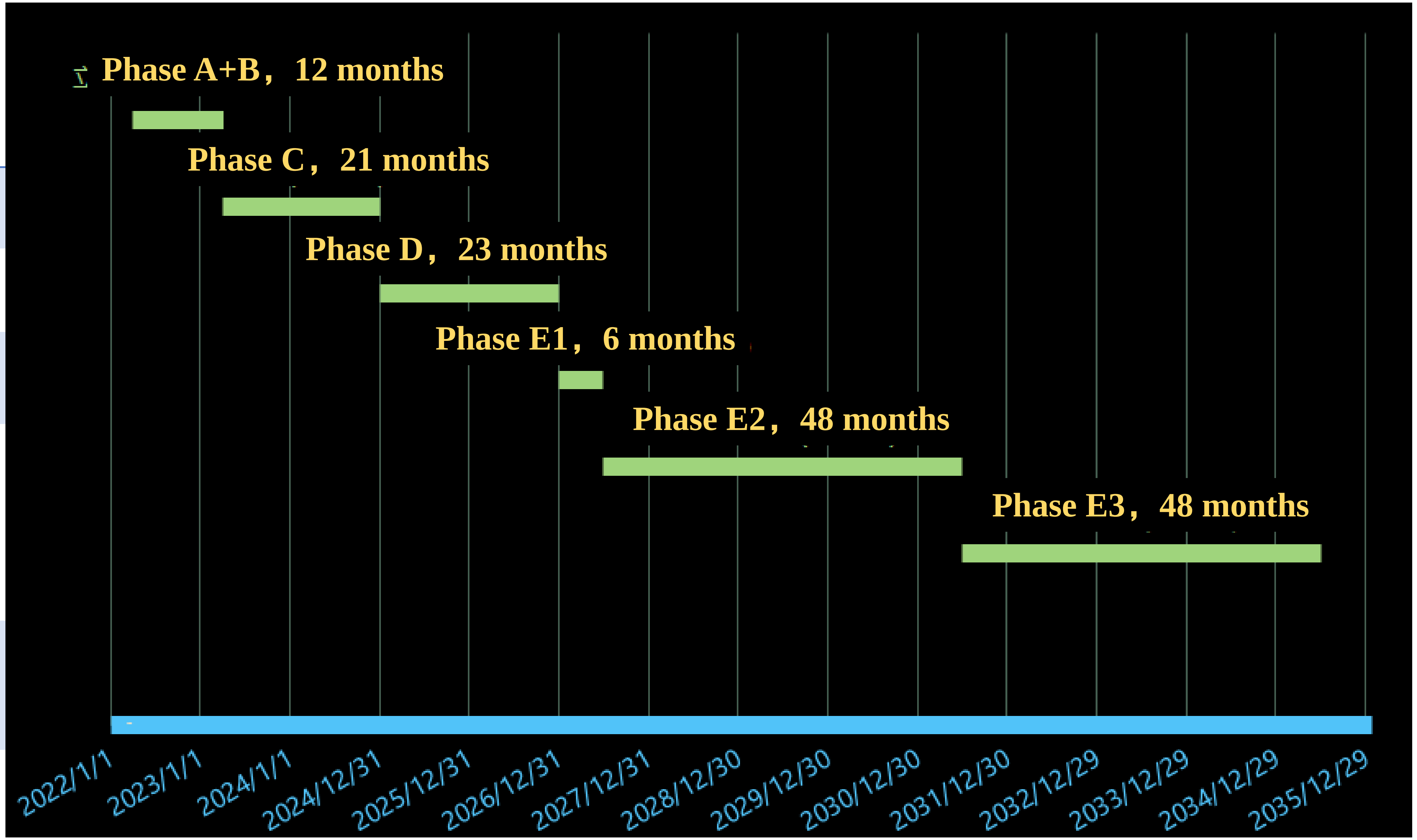
ET will be the first exoplanet space mission in China

- Key science objectives： **the First Earth 2.0；Terrestrial Planet Formation； Cold Planets**
- To potentially discover the first habitable Earth like planets around sun-like stars; to provide candidates for follow-up biosignature observations and characterization

ET Development Plan

The ET spacecraft is expected to be launched in 2026

Phase	Duration (month)	Time (Assume T0=2022/3/31)
Phase A+B	12	2022/4-2023/3
Phase C	21	2023/4-2024/12
Phase D	24	2025/1-2026/12
Phase E1 (Launch and transfer)	6	2027/1-2027/6
Phase E2 (Mission)	48	2027/7-2031/6
Phase E3 (Extended)	48	2031/7-2035/6



Summary

- **No Earth 2.0s have been identified yet!**
- **Transit method is the most promising one to potentially detect Earth 2.0s**
- ET is expected to detect **~17 Earth 2.0s while** follow-up of some Earth 2.0s around bright solar type stars may be able to detect biomarkers in transit planet atmosphere
- ET is expected to **detect ~30,000 planets, including 5000 terrestrial planets**, and **~1000 cold and free-floating planets**, and provide **~1/4 number of mass measurements** for free-floating planets with simultaneous observations with KMTNet